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Physics Analysis

John Womersley

CERN-Fermilab Hadron Collider Physics Summer School
August 9-18, 2006

Outline

- Some basics
- Simulation tools
- Case studies to illuminate some issues
  - Top at the Tevatron
  - Single top at the Tevatron
    - Including a digression on multivariate techniques
  - Top at UA1
- Analysis "after discovery"
- Systematic errors
- Conclusions

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Basics

- Hadron Colliders – especially those that allow access to a new energy regime – are machines for discovery
  - In the case of the TeV scale, this is reinforced by the fact that the known SM forces and particles violate unitarity at around 1 TeV: there must be something new (if only a SM Higgs)
- Discovery means producing convincing evidence of something new
- In most of our models this means the production of new particles
  - (though this need not be the only way)
- Goals of analysis in this case: produce this evidence
  - Separation of a signal from the backgrounds **Today**
  - Show that the probability of this signal arising from known sources is small
    - Demonstrate that the backgrounds are understood
    - Statistics and systematics

Much more from Louis Lyons tomorrow

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Access to the data: typical setup

Raw data

↓ Centrally managed reconstruction – batch-like, only once if possible

Reconstructed data

↓ skimming – copying subsets of data

Skim dataset

↓ compress, possibly after re-reconstruction

Analysis dataset(s)

This is what you work on

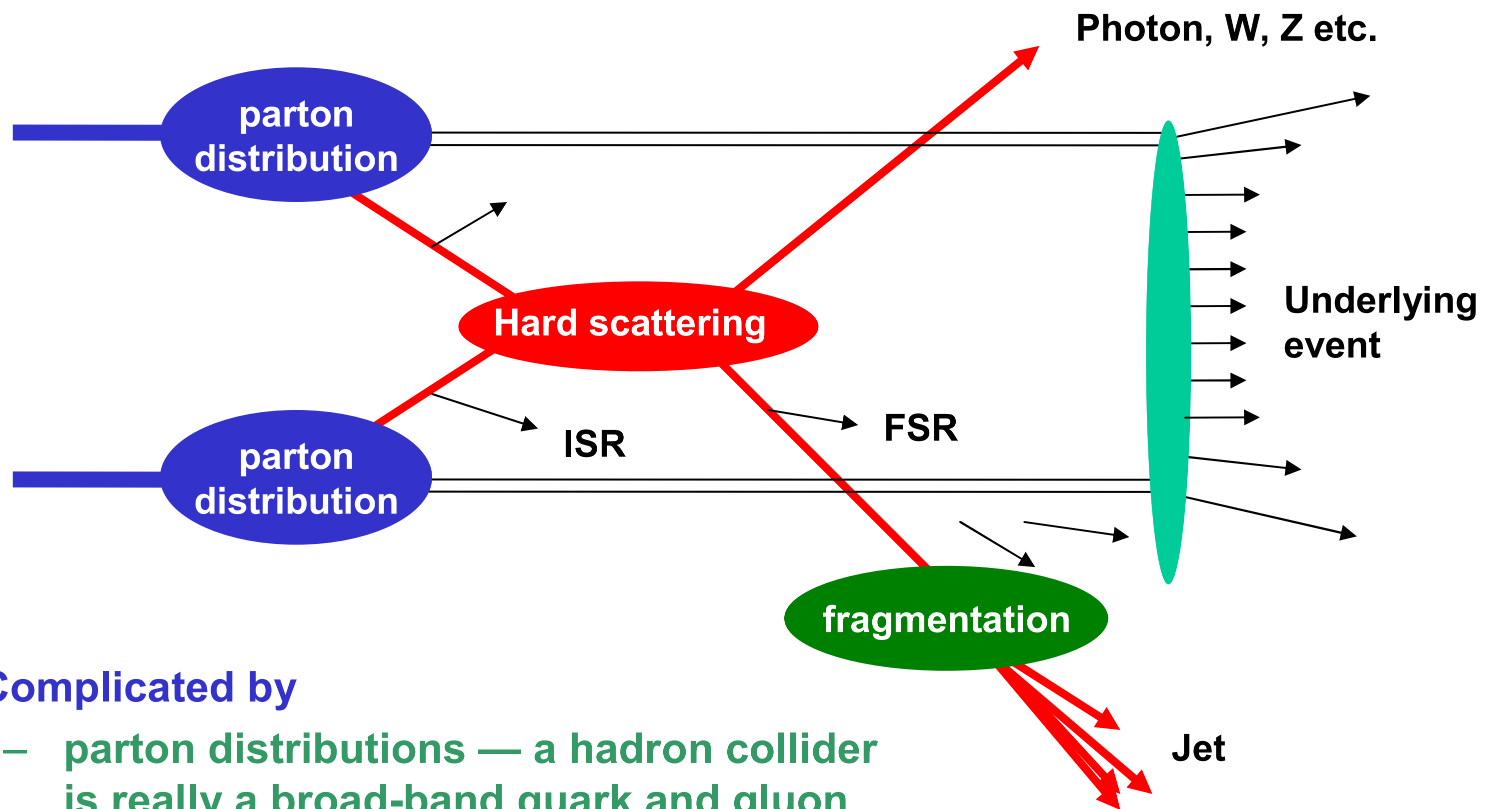
Should be

- small enough for rapid turnaround
- large enough to enable background estimation
- have clear parentage (so luminosity, trigger efficiency well defined)
- use standard definitions of objects unless a very good reason not to

Simulation

- In order to convince the world that you have produced something new, or to set limits on a proposed model, you need to understand
  - What the standard model processes we already know about would look like in your detector
  - How your detector would respond to the proposed model (and thus that non-observance of a signal is significant)

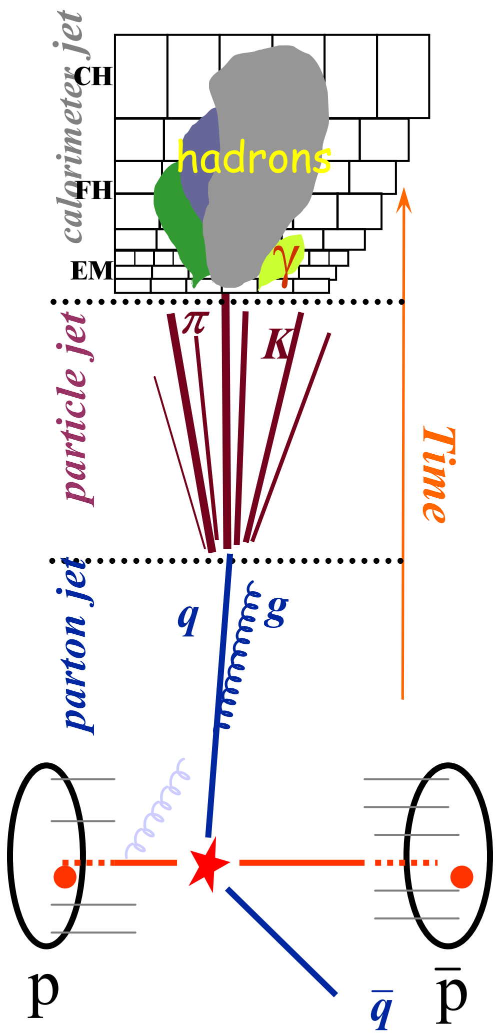
Simulating hadron-hadron collisions



- Complicated by
  - parton distributions — a hadron collider is really a broad-band quark and gluon collider
  - both the initial and final states can be colored and can radiate gluons
  - underlying event from proton remnants

Simulation tools

- A “Monte Carlo” is a Fortran or C++ program that generates events
- Events vary from one to the next (random numbers) — expect to reproduce both the average behavior and fluctuations of real data
- Event Generators may be
  - parton level:
    - Parton Distribution functions
    - Hard interaction matrix element
  - and may also handle:
    - Initial state radiation
    - Final state radiation
    - Underlying event
    - Hadronization and decays
- Separate programs for Detector Simulation
  - GEANT is by far the most commonly used



Things to remember – 1

- Event generators
  - May or may not generate additional jets through parton showering
  - May or may not treat spins properly (should you care?)
  - May or may not get the cross section right
    - NLO much better than LO – but sometimes no choice

- Be careful over things like
  - You can’t necessarily just add (for example) a W+1 jet simulation and W+2 jets and W+3 jets to model a W + n jet signal. Likely to be double counting.
  - You can’t necessarily just run a W+1 jet simulation and generate the extra jets through parton showering either…

Things to remember – 2

- Detector simulation
  - Your detector simulation is only as good as the geometrical modeling of the detector
    - Are all the cables and support structures in place?
    - Example of DØ silicon detector
  - While EM showers can be modeled very well (limited by the above) hadronic shower simulation is acknowledged to be an imperfect art
  - Short time structure in current detectors adds another dimension
    - Nuclear de-excitations, drift of charge in argon can be slower than bunch crossing time

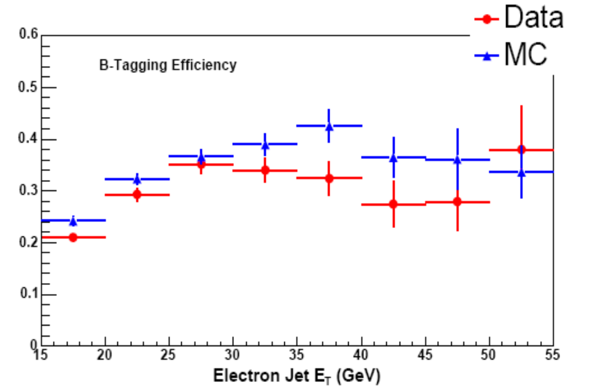
- In general
  - You can probably get the average behavior right
  - Don't blindly trust tails of distributions or rare processes
    - random numbers may not populate them fully
    - modelling not verified at this level
      - e.g. I would be wary of an MC estimate of the probability for a jet to be reconstructed as a photon – a 10^{-3} or 10^{-4} probability

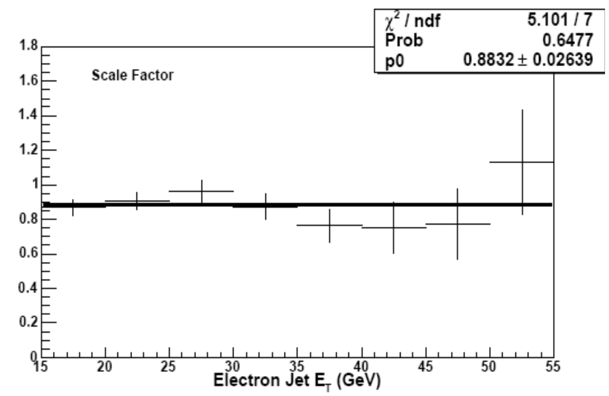
Example: b-tagging

- To correctly simulate the b-tagging efficiency of the detector requires proper modelling of
  - Alignment of the silicon tracking detector
  - Processes of charge deposition
  - The nature and amount of material in the tracking volume
    - Can use e^+e^- conversions
  - Pattern recognition
  - Track-finding efficiencies

- Better to determine efficiencies from data
  - calibration data must be collected at appropriate E_T and η

In the end: "Monte Carlo scale factors"





Simulation: bottom line

- Don't think of your simulations so much as predictive tools but as multidimensional parameterisations of your knowledge of the detector and SM processes

- Like any parameterisation, you have no real right to use it without having verified that it works in the region of phase space that you care about

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Case Study 1

Top at the Tevatron

How can we extract a signal for top?

- Properties of top are predicted by theory, in this case the SM, except for its mass (just like the Higgs ☺)
  - but even before discovery we had a good idea of the top mass, from limits set by earlier negative searches and from EW fits (just like the Higgs ☺)

- Production cross section
  - Colored particle – expect relatively high cross section
  - Pair production turns out to be the dominant mode $\bar{q}q \rightarrow \bar{t}t$
  - QCD, color octet, spin ½: $\rightarrow$ 5 – 10 pb in $\bar{p}p$

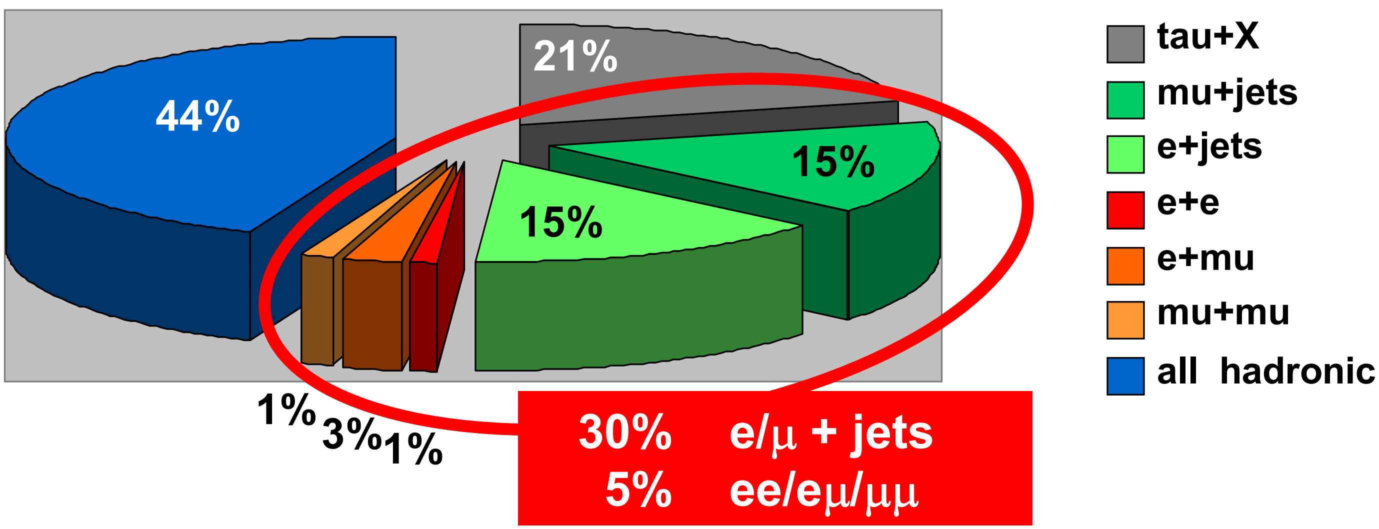
- Decay mode
  - In SM, weak decay
  - CKM matrix elements constrained by unitarity
  - ~100% to $t \rightarrow Wb \rightarrow$ known decay modes of W

- Massive object $\rightarrow$ high p_T decay products

$t\bar{t}$ final states

- Standard Model: $t \rightarrow Wb$ dominates

t	W^+	$l^+\nu$	$q\bar{q}$	$l^+\nu$	$q\bar{q}$
	b	b	b	b	b
$\bar{t}$	W^-	$l^-\bar{\nu}$	$l^-\bar{\nu}$	$q\bar{q}$	$q\bar{q}$
	$\bar{b}$	$\bar{b}$	$\bar{b}$	$\bar{b}$	$\bar{b}$



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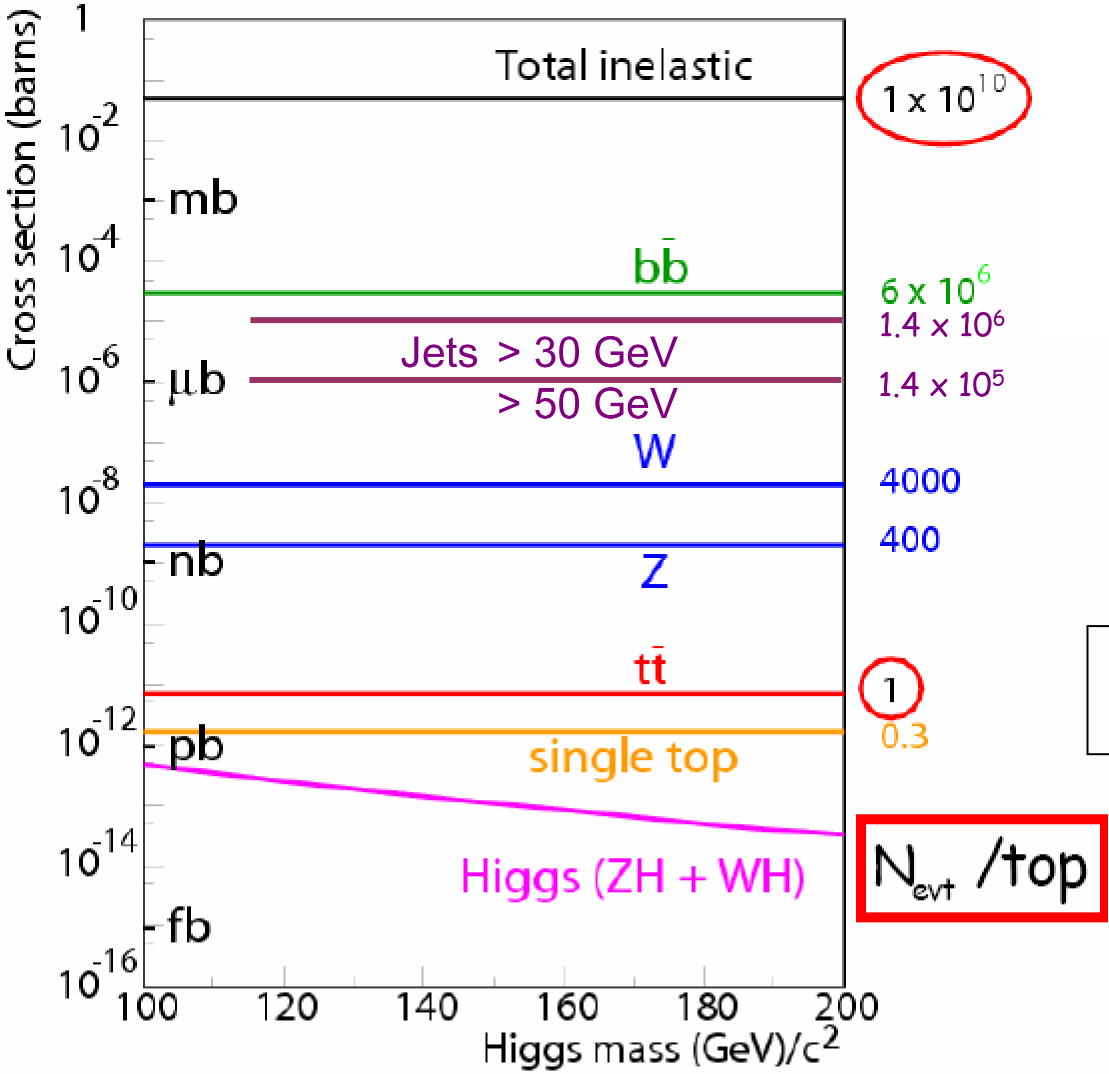
Lepton signatures



Cross sections for high p_T jets

Cross sections for high p_T leptons

10^2 - 10^3 times more high p_T jets than high p_T leptons

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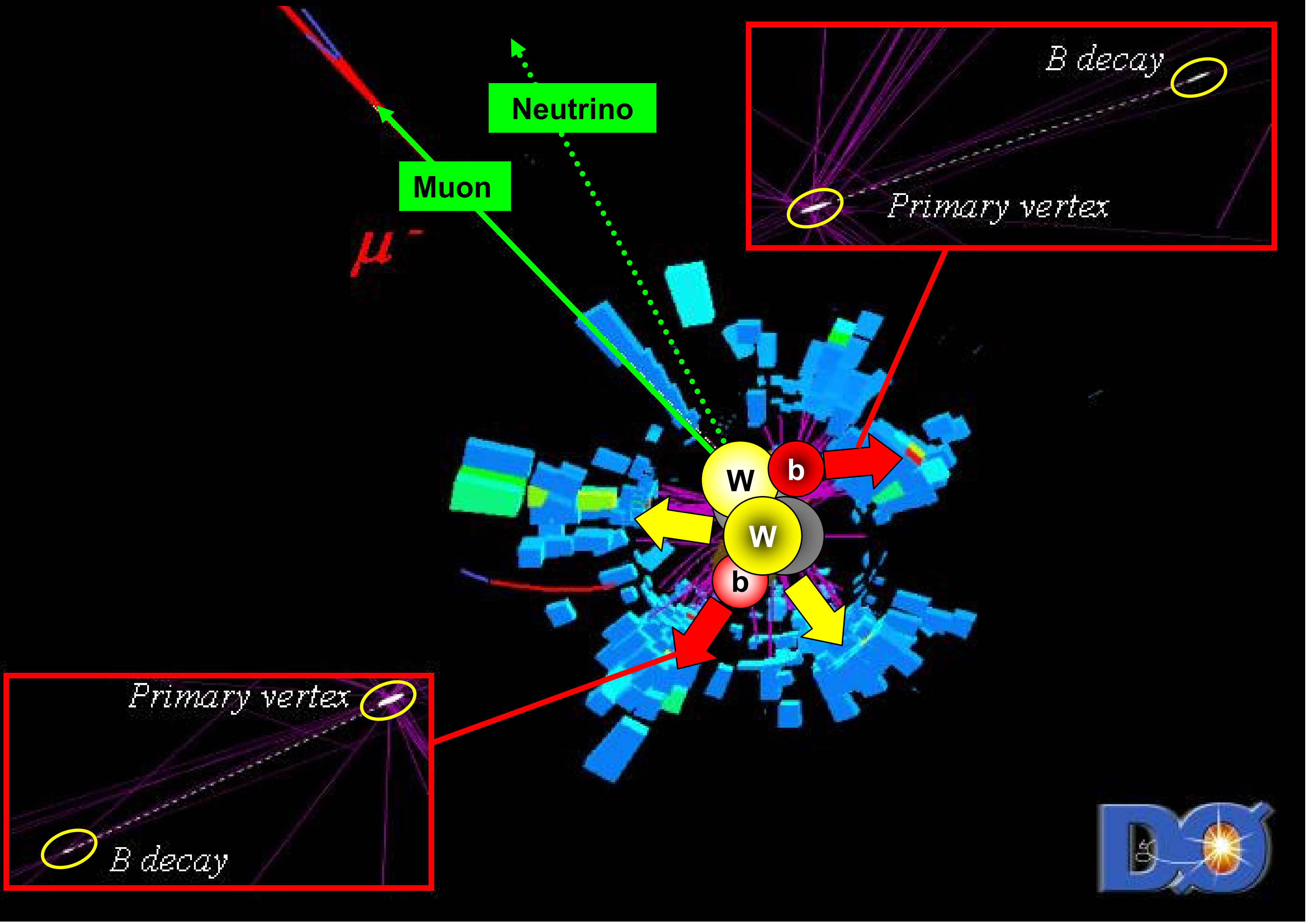
Final state signatures

The best bet seems to focus on the following two modes:

- **"Lepton + jets"**
  - **One W decays leptonically**
  - **High p_T lepton, two b-jets and two light quark jets + missing E_T**
    - **Good balance between signal and background**

- **"Dilepton"**
  - **Both W's decay leptonically**
  - **Two high p_T leptons, two b-jets + missing E_T**
    - **Only 1/6 of the signal rate but much lower backgrounds**

How to catch a Top quark



So…

- This kind of signature requires an excellent understanding of the whole detector
  - Triggering, tracking, b-tags, electrons, muons, jets, missing E_T
  - Performance must be understood and modelled
- and of the likely backgrounds

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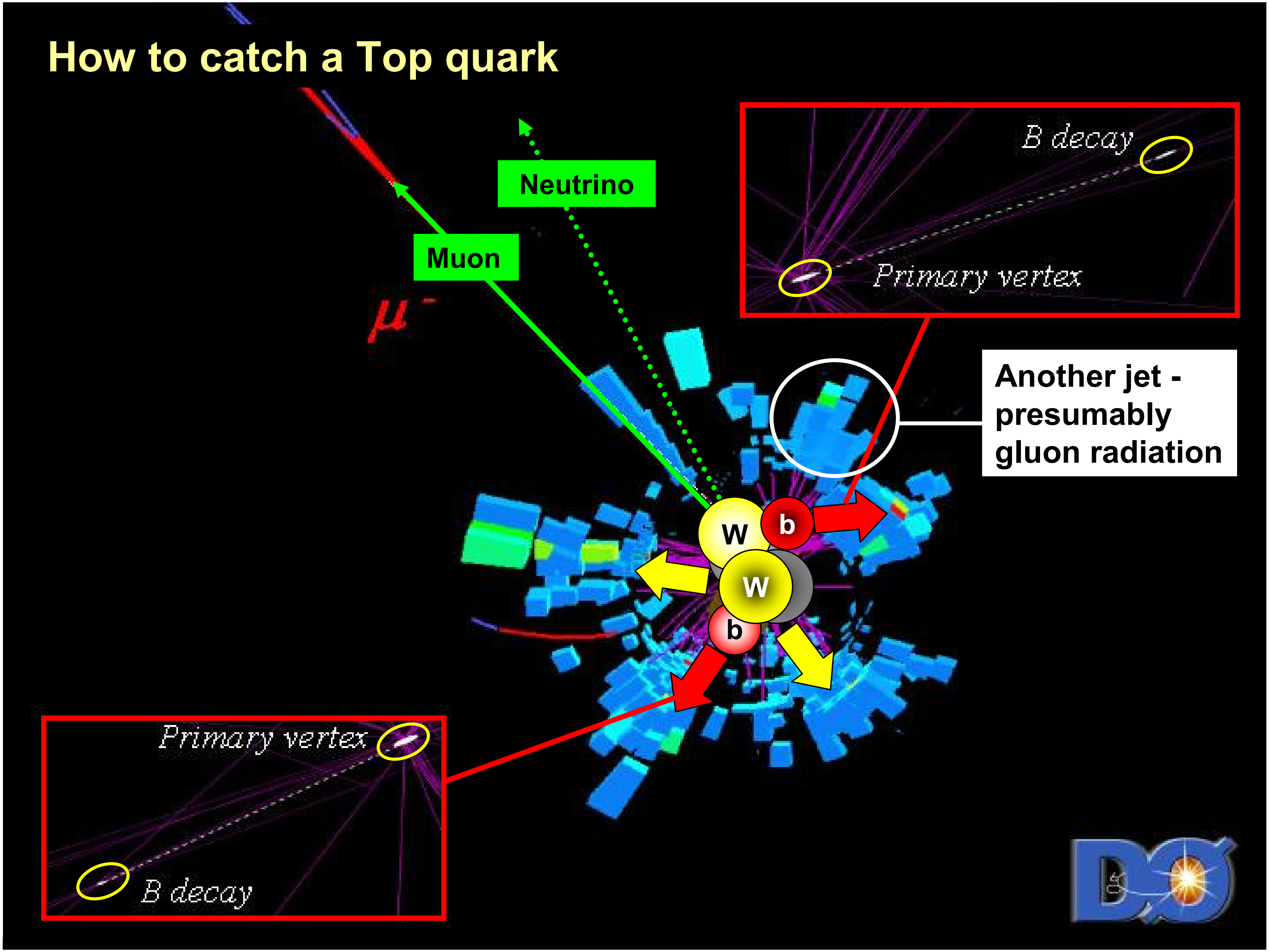
Lepton + jets

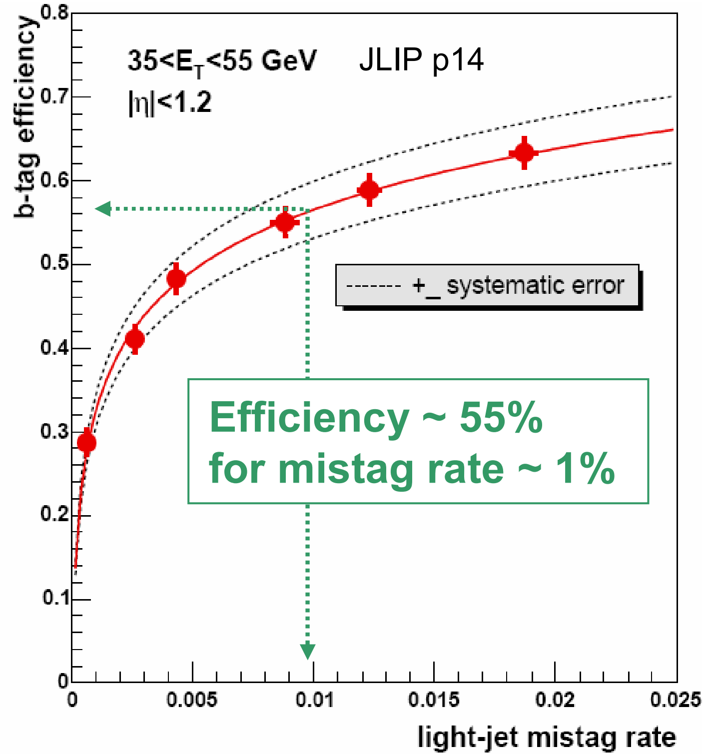
- Require isolated lepton + ME_T + jets
  - Dominant backgrounds will then be W+jets processes
- There are 4 quarks in the $t\bar{t}$ partonic final state. Require 4 jets?
- # partons $\neq$ # jets!
  - Get more jets from
    - gluon radiation from initial or final state
  - Get fewer jets from
    - Overlaps (merged by reconstruction)
    - Inefficiencies or cracks in the detector
    - Jets falling outside acceptance in η
    - Jets falling below p_T cut



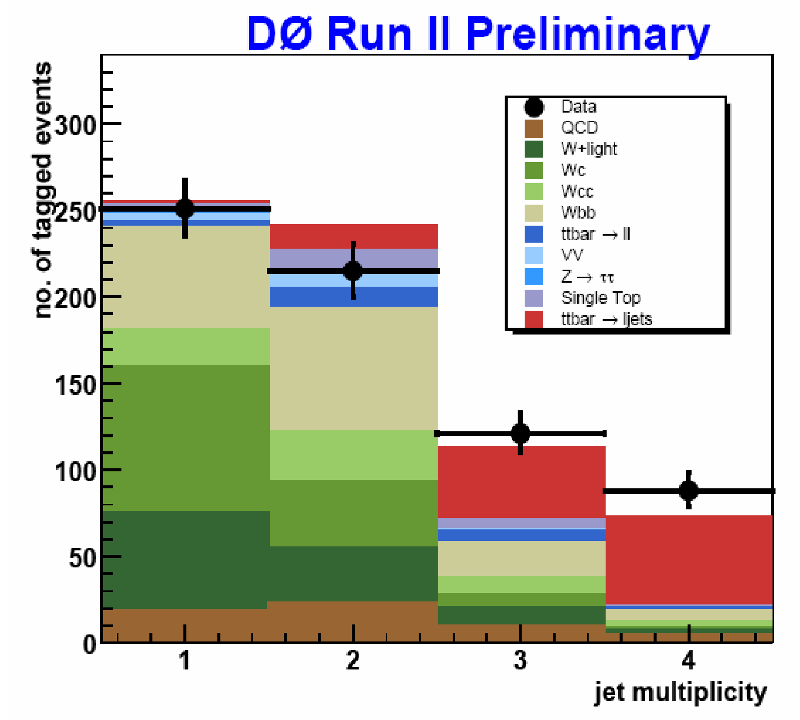
How to catch a Top quark
Neutrino
Muon
μ^-
B decay
Primary vertex
Another jet - presumably gluon radiation
W
b
W
b
Primary vertex
B decay

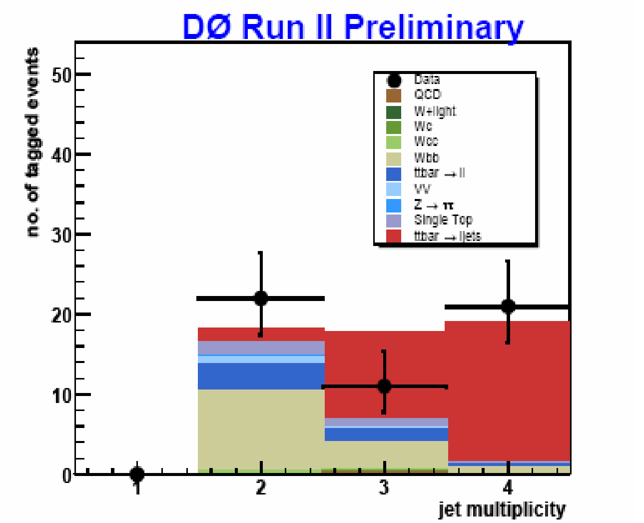
How many b-tags?

- Since typical b tagging efficiency ~ 0.5, then for a final state with two b jets
  - Prob(2 tags) ~ 0.25
  - Prob(≥ 1 tag) ~ 0.75
- Best number to ask for depends on signal:background and nature of background
  - is it dominated by real b's or not?
  - If the signal has two real b jets, and so does the main background, then there is little to gain from asking for a second b-tag
- In the top sample, requiring ≥ 1 tag is good
- But want to look at ≥ 0 and ≥ 2 tags as well, to check that all behaves as we expect given the signal and background composition we estimate



Lepton + jets signals





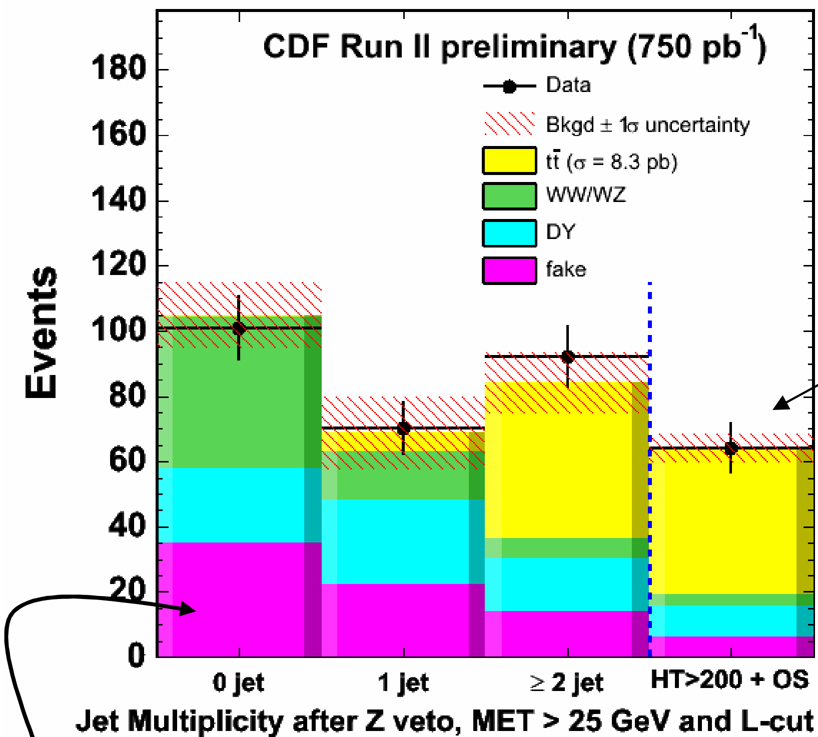
Analysis with 2 tags

N_{jets} = 1, 2
Control region (little signal)
Verify background modelling:
tagging efficiencies from data
b:c:light q ratio from MC

N_{jets} = 3, 4
Signal region

Combine results (including correlations) to get best estimate of cross section

Dileptons



Signal selection

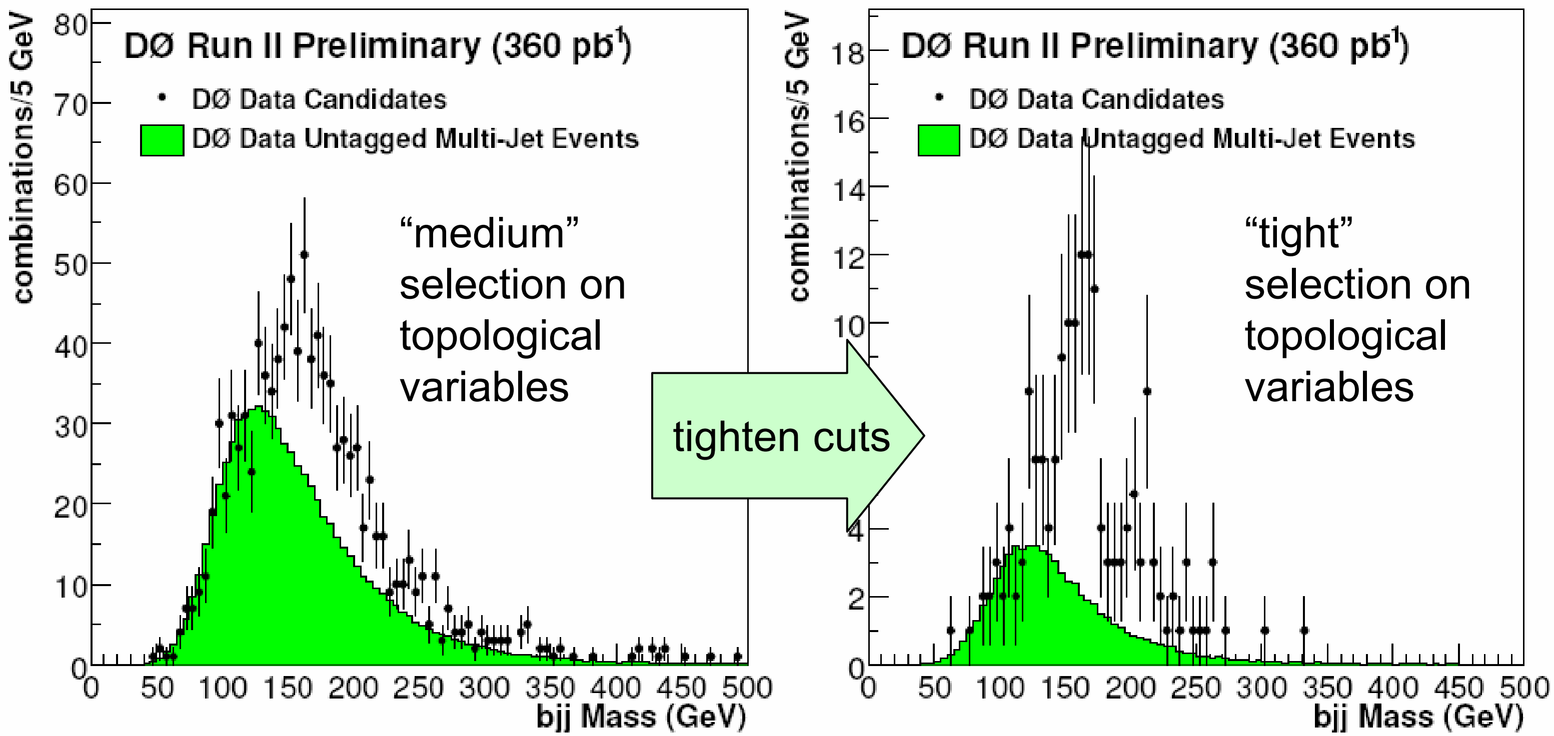
- Note non-negligible contribution from fake (misreconstructed) leptons
  - Recall that # jets/# leptons ~ 10^3
  - So unless Prob(jet $\rightarrow$ reconstucted lepton) << 10^{-3} , cannot be ignored
    - Fake muons from calorimeter punchthrough
    - Fake electrons from jet $\rightarrow$ leading π^0 + track overlap

Feeling lucky, punk?

Then we'll look for top → all jets

Top → jets

- **Six jets final state with two b-jets**
- **Decay of massive objects: tend to be central, spherical, acoplanar events**
- **Only leading order QCD calculation for $\bar{p}p \rightarrow 6$ jets: use data for bkg**



- **Impressive to see a signal but not (yet) in itself a discovery mode**

Case Study 2

Single Top at the Tevatron

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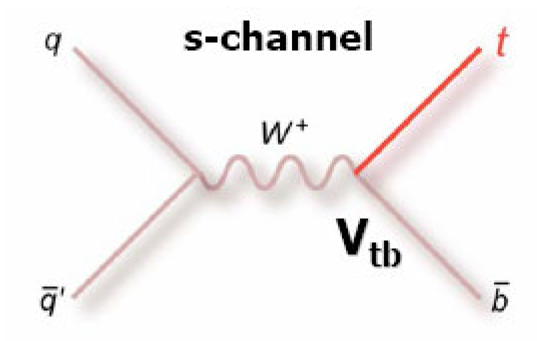
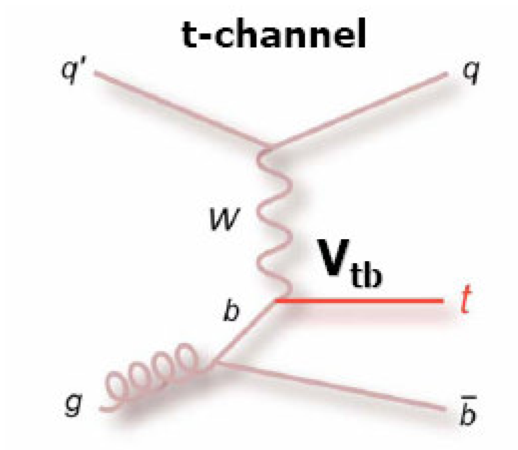
Single Top production

- Probes the electroweak properties of top and measures CKM matrix element $|V_{tb}|$
- Good place to look for new physics connected with top
- Desirable to separate s and t-channel production modes:



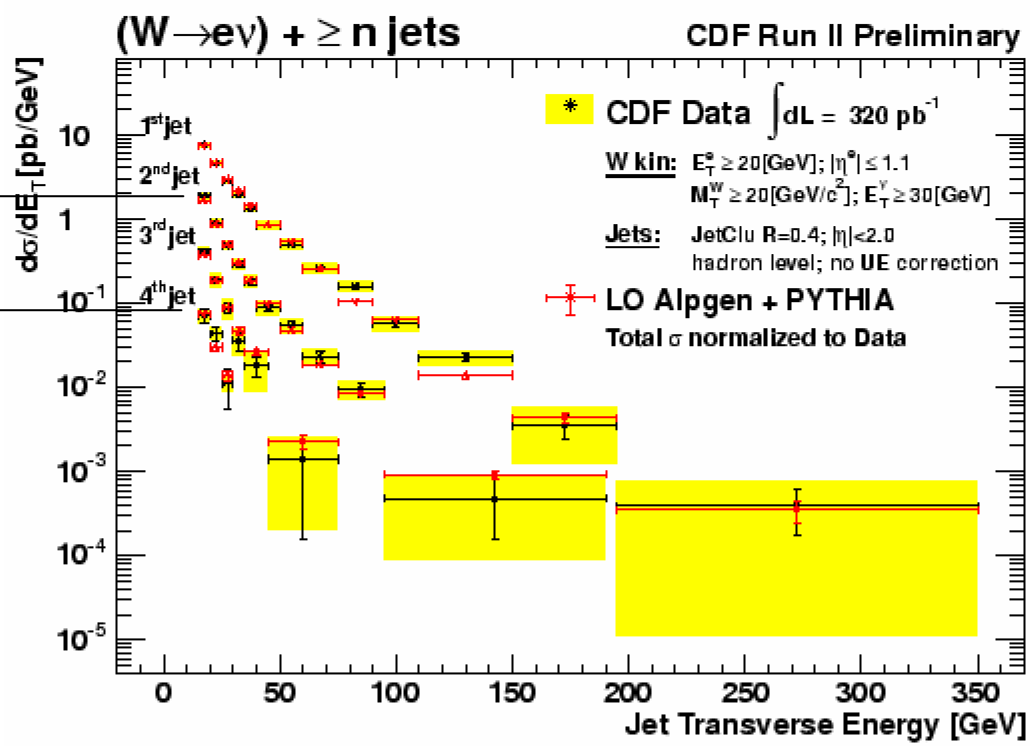


- The s-channel mode is sensitive to charged resonances.
- The t-channel mode is more sensitive to FCNCs and new interactions.
  - Expected cross section is about 1 pb (s-channel) and 2 pb (t-channel)

Backgrounds

- Final state is Wbb → lepton + ME_T + two b-jets
- Signal to background much worse than for $t\bar{t}$
  - Basic reason:
    tt is a “W+4 jet” signal
    single top is a “W+2 jet” signal

Factor ~ 25 higher cross section



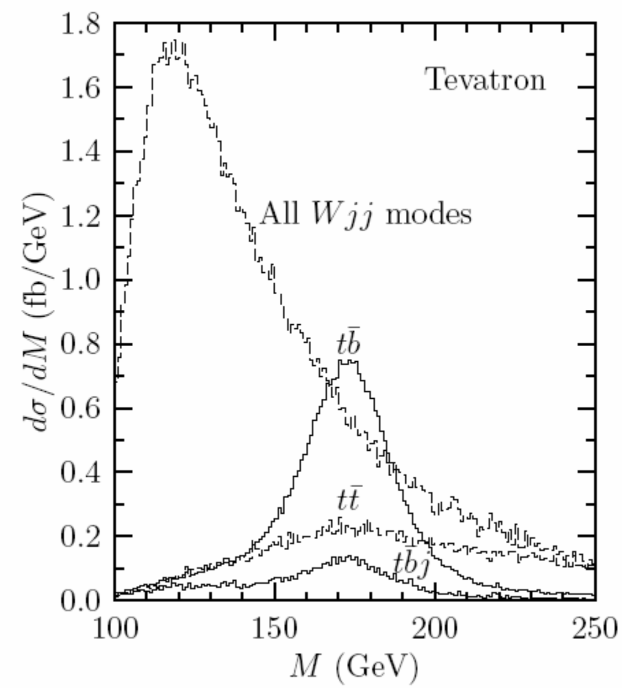
1998...

- **hep-ph/9807340**

hep-ph/9807340
July 1998

Single-top-quark production at hadron colliders

T. Stelzer, Z. Sullivan and S. Willenbrock
Department of Physics
University of Illinois
1110 West Green Street
Urbana, IL 61801

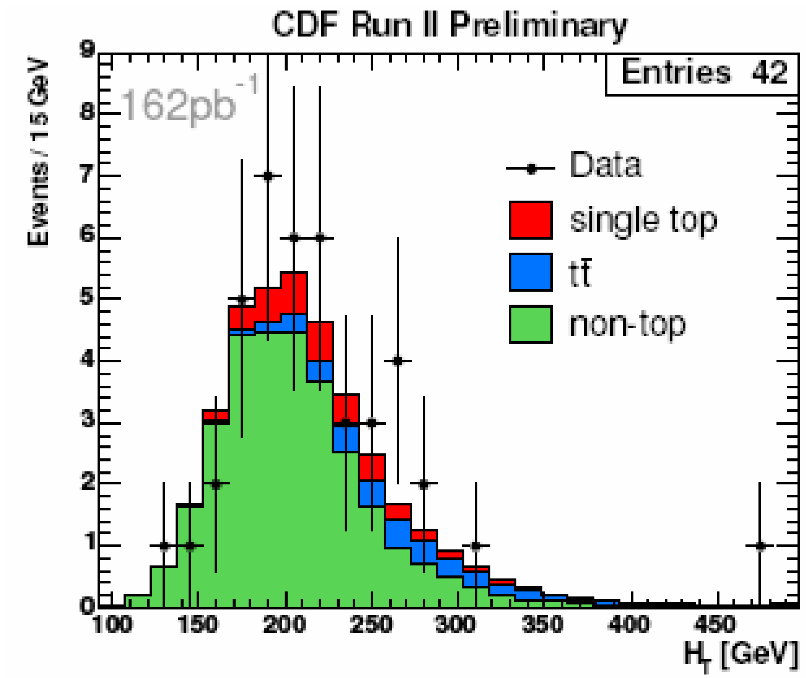


- **Signal: background ~ 1**
- **"5σ signal in 500 pb^{-1}"**

2005…

- **Real life**

  signal:background ~ 0.1 in this example



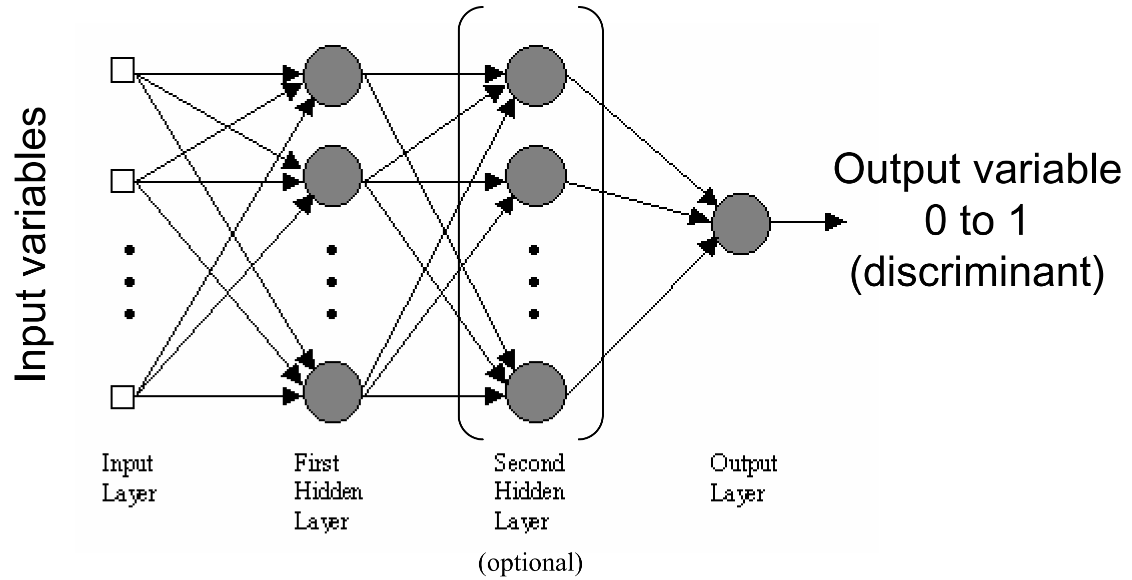
- **What happened?**
  - **Reality is not a parton level simulation – lose signal**
  - **Real b-tagging (lower efficiency at lower p_T)**
  - **Real jet resolutions (jets not partons) and missing E_T resolution**

- **Life's a bitch. And it's almost always worse than your TDR.**

Never fear – help is at hand

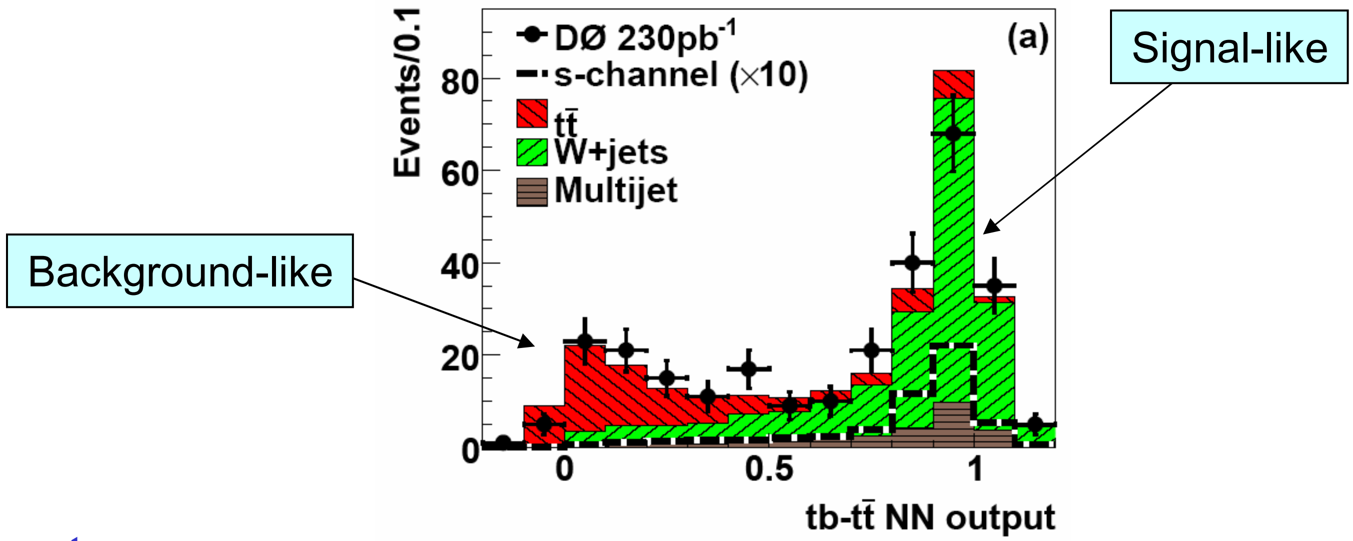
Neural Networks

- **"Artificial" (i.e. software) Neural Network**



- **Algorithm is stored as weights in the links**
- **Network is trained with samples of "signal" and "background(s)"**
  - **Samples repeatedly presented to the network**
  - **Outcome compared with desired**
  - **Link strengths adjusted**

- **What you get out (example)**



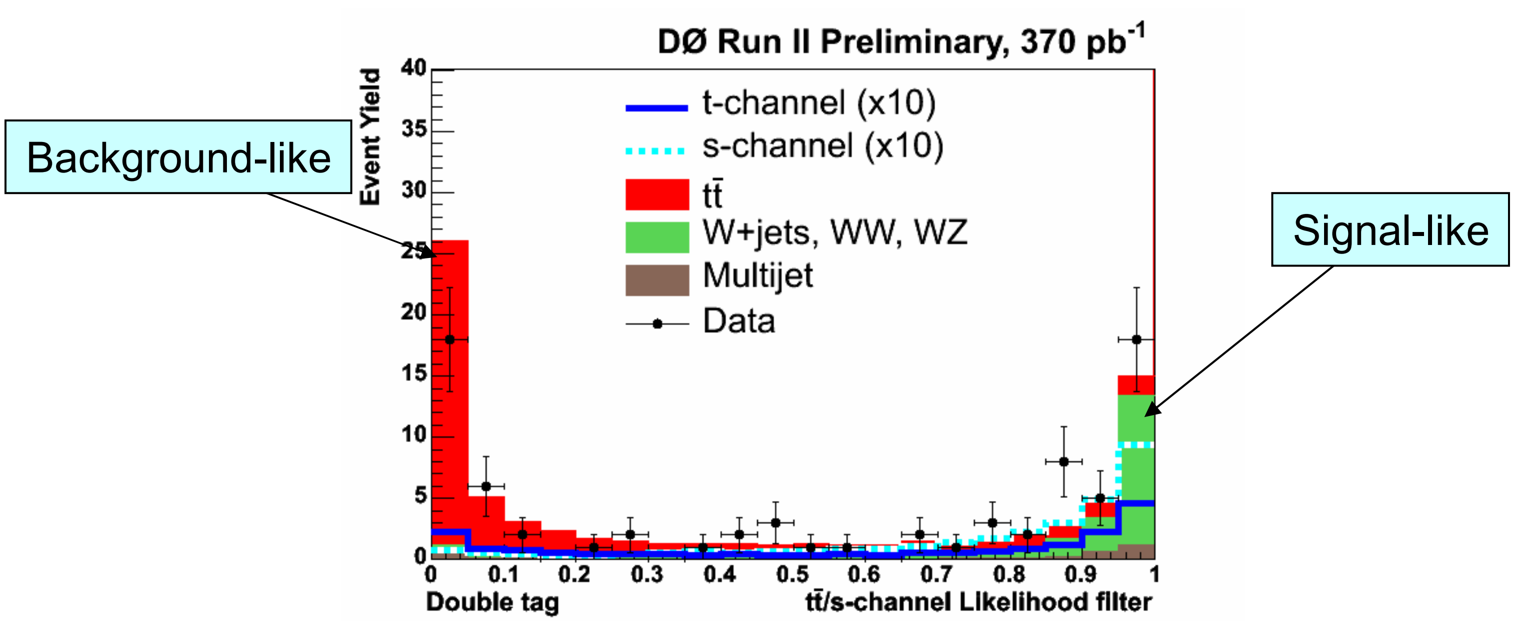
- **Advantages**
  - **Develops non-linear selection criteria on combinations of variables**
  - **A way to discriminate between S & B when you have many, correlated variables none of which individually show a clear separation**
- **Disadvantages**
  - **Often seen as something of a black box**
  - **Only as good as your "training" samples**
    - **reliance on simulations?**

For single top, gave a factor of 2 better sensitivity than the cut-based analysis

Other multivariate techniques

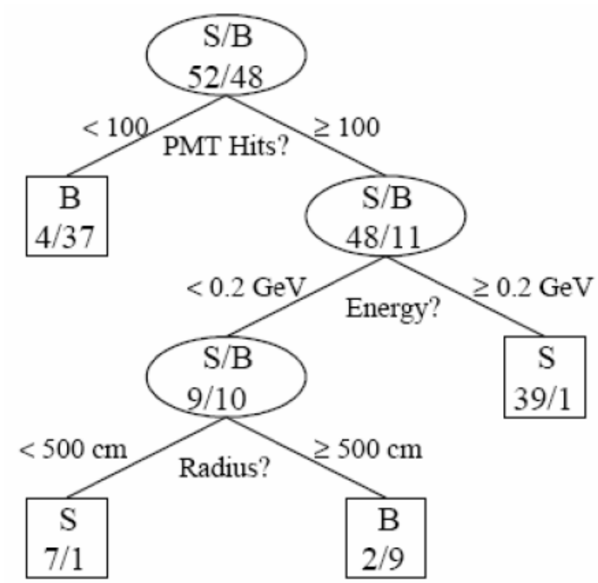
- **Likelihood Discriminants**
  - Less of a "black box"

$$L(x) = \frac{P_{signal}(x)}{P_{signal}(x) + P_{background}(x)}$$



  - For single top, analysis using 4 likelihood discriminants has comparable sensitivity to NN analysis

- **Decision trees**
  - Rather new in high energy physics – miniBooNE is using
  - Some attractive features (again, "not a black box")



Split data recursively until a stopping criterion is reached (e.g. purity, too few events)

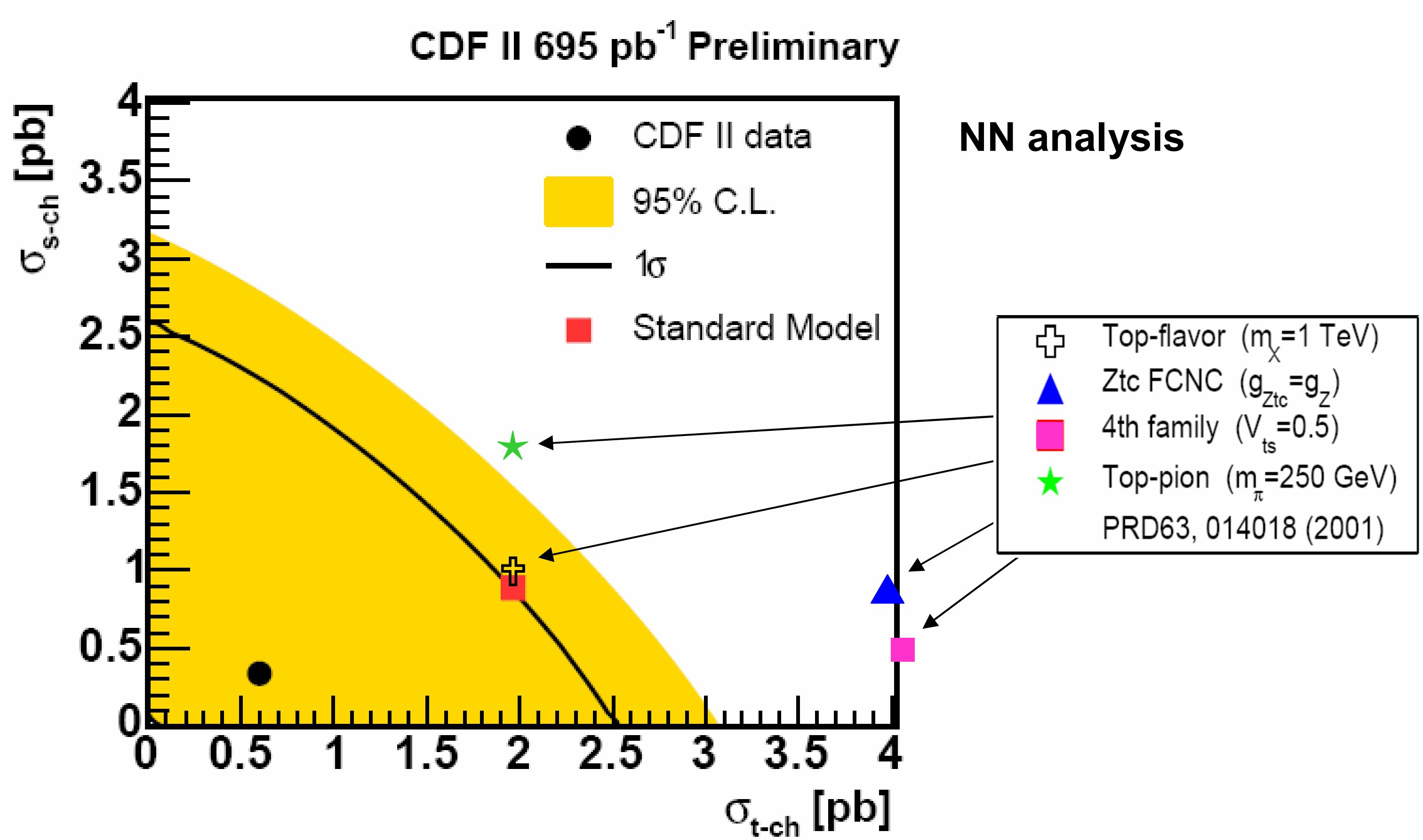
All events end up in either a "signal" or a "background" leaf

  - "boosted" and "bagged" decision trees

- **Many more: Support vector machines, Bayesian NN, genetic algorithms,…**
  - http://www.pa.msu.edu/people/linnemann/stat_resources.html

Back to single top

- Not yet able to see SM rate, but starting to disfavor some models



- A few inverse femtobarns for discovery

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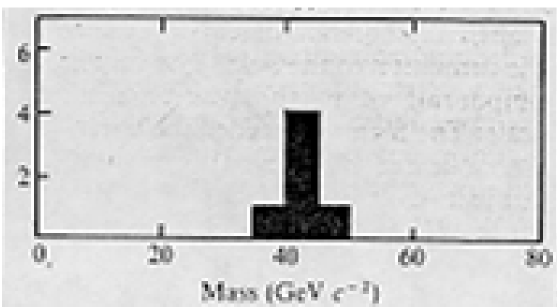
Case Study 3

Top at UA1

Nature, July 1984



Distribution of measured top quark mass.

CERN comes out again on top

With the discovery of the electroweak bosons ($W^{\pm}$ and Z^0) in the bag, CERN now announces the discovery of the quark called top. *What will come next?*

THE Matthew principle — "to him that hath shall be given" — is working in favour of CERN, the European high-energy physics laboratory at Geneva, and of the UA1 collaboration which, at the end of last year, announced the discovery of the $W^{\pm}$ and Z^0 particles which mediate the electroweak interaction. Last week, the same 80-strong collaboration, under the leadership of Carlo Rubbia, announced the discovery of the missing sixth quark, called *top*, long-predicted but hitherto elusive. By doing so, they have put yet another cap on the electroweak theory while restoring a seemly symmetry to the evolving picture of quarks as the elementary constituents of the material Universe.

The new development at CERN follows almost exactly along the lines expected (and described, for example, by Dr F. Close in his comment on the electroweak bosons, see *Nature* 303, 656; 1983). The source of the sixth quark is a charged boson, W^+ or W^-, first recognized at CERN by their decay into an electron (with electrical charge of the same sign), with excess momentum carried away by a neutrino. Events of this kind accumulated at CERN in the past two years have amply confirmed that the mass of the $W^{\pm}$ particles is that predicted by the electroweak theory, the equivalent of 82 ± 2 GeV. The neutral member of the trio of heavy bosons, the Z^0, is less frequently produced (by a factor of about 10) in the proton–antiproton collisions at CERN, has a greater mass (to the tune of an extra 12 GeV) and is chiefly recognizable by its decay into a pair of electrons, positive and negative.

Although the chief decay path for the $W^{\pm}$ bosons is that by which their existence was first recognized, it has from the outset been accepted that decay schemes leading to the production of quarks should be recognizable alternatives. Briefly, a W^+ particle should be capable of yielding a *top* and the antimatter version of a *bottom* quark. (W^- would then yield anti-*top* and anti-*bottom*.) For the past two years, there has been general agreement on the way in which these particles could be recognized. The *bottom* quark (or anti-quark) would itself decay into a narrow jet of nuclear matter — pi-mesons for example. And the *top* quark, with a greater mass, would first decay into *bottom* and then yield another jet of particles, this time less tightly collimated. Since the first evidence for $W^{\pm}$ particles began to accumulate at CERN, people have been wondering whether some of the events recorded by UA1 were signs of decay of this kind. Six events have now been unambiguously identified as the decay of $W^{\pm}$ into *top* and *bottom*; the mass of *top*, estimated at 40 GeV, remains substantially uncertain.

For the time being, however, the proof that *top* exists is enough to be going on with. In the simplest terms, the asymmetry that has now been removed is that between the set of known electron-like particles and the set of quarks. For reasons which are frankly not understood, the natural world contains not just one material lepton, the electron (and its anti-particle, the positron), but two others, the muon and the tauon (each with its oppositely charged anti-particle). With each of these three leptons is associated a distinctive neutrino, recognizably different in the mechanisms by which they interact with matter but, on present form, not otherwise distinguishable — they have no electrical charge and no mass. But neutrinos are, like electrons, true leptons — they are involved symmetrically with electrons, muons and tauons in the working of the weak nuclear interaction (as in beta decay).

6
4
2
0 20 40 60 80
Mass (GeV c^{-2})

Distribution of measured top quark mass

The idea that quarks should also come in pairs, and that there should be as many pairs of quarks as there are pairs of leptons, is more an act of faith than a consequence of theoretical expectation. To be sure, if the world is symmetrical in this way, it is possible to build neater theories, more symmetrical than would otherwise be the case. But that is merely a sign that, in its foundations, theoretical physics remains Pythagorean.

Phenomenologically, the need for symmetry has nevertheless been urgent since the late 1940s. The recognition of the difference between the pi-meson and the muon first raised the puzzle of the apparently superfluous lepton. The discovery (in cosmic rays) at the same time of a new kind of hadronic (nuclear) matter, called *strange* because that is what it was, set the scene for Gillman's radical proposal that mesons such as the pi-meson, but also the *strange* particles themselves, are pairs of quarks — the pi-meson is a pair called *up* and *down* for example. But nucleons, such as protons and neutrons, and other baryons, are combinations of three quarks — the proton, for example, is two *up* quarks and one *down*. The partner of *strange*, discovered only in 1975, is *charm*. Evidence for *bottom*, also known as *beauty*, was found in 1977 in the proton–proton collisions arranged at Fermilab, where a meson whose mass exceeds the equivalent of 9.4 GeV was surmised to be a bound state of *bottom* and anti-*bottom*.

The quark called *top* (and also, sometimes, *truth*) is thus the missing member of the series. Its appearance has been expected for some time, but is no less welcome to the closet-Pythagoreans on that account. What will, in the short term, matter more is that the steady refinement of the mass now on the cards should make possible a degree of certainty about the nature of some still disputed hadronic particles and resonances. While the electroweak theory itself has been further confirmed, CERN and its UA1 collaboration have provided a more stringent test both of theories of quantum chromodynamics (theories of the strong nuclear interaction) and of Grand Unified Theories (which would roll that together with the electroweak theory but not — yet — with gravitation). Only time will tell whether the outcome is any confirmation of some version or another surprise — yet another pair of leptons or quarks, for example.

Inevitably, the question will arise in Britain whether the discovery of the *top* quark at the collaborative high-energy physics laboratory will bear on the decision, now delegated to a committee under Sir John Kendrew, on whether Britain should continue to collaborate. The arguments run both ways. The discovery of *top* means that CERN's list of unattained achievements has been reduced by one, but at the same time the laboratory's reputation for success has been enhanced. It is, however, unlikely that the committee's recommendations will be determined by scalp-counting of this kind, while high-energy physicists will properly draw attention to the need, now, for the careful understanding of the relationships between the six quarks that will come only from more careful measurements of the decay schemes now recognized, and of the alternatives still to be found.

John Maddox

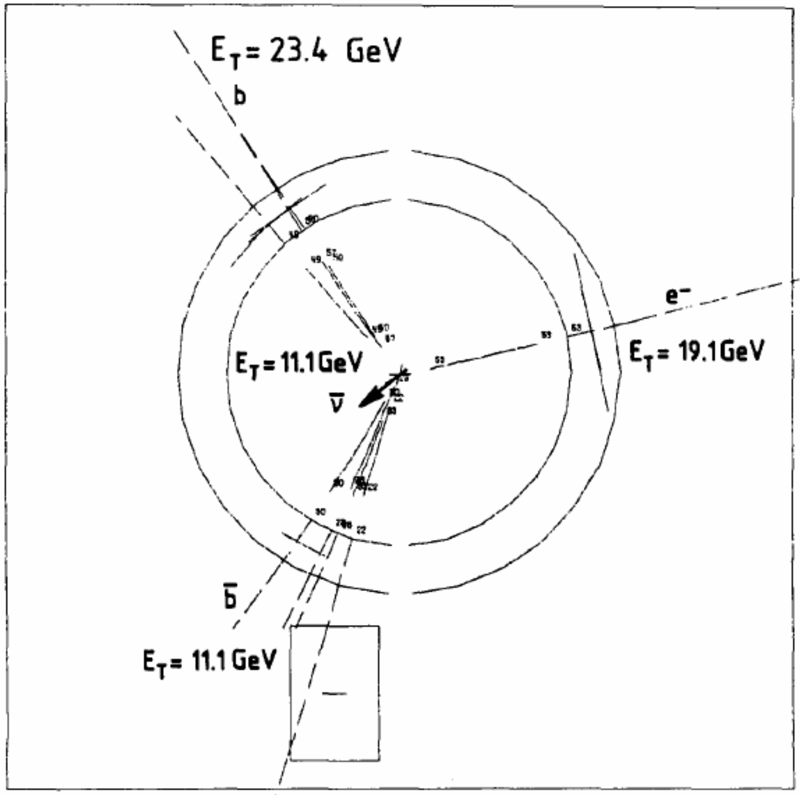
Top at UA1

- **Associated Production of an isolated, large transverse momentum lepton (electron or muon) and two jets at the CERN $\bar{p}p$ Collider**
  G. Arnison et al., Phys. Lett. 147B, 493 (1984)

- **Looking for**

  $\bar{p}p \rightarrow W$
  $\quad \lfloor\!\rightarrow b\,t$
  $\quad\quad \lfloor\!\rightarrow b l \nu$

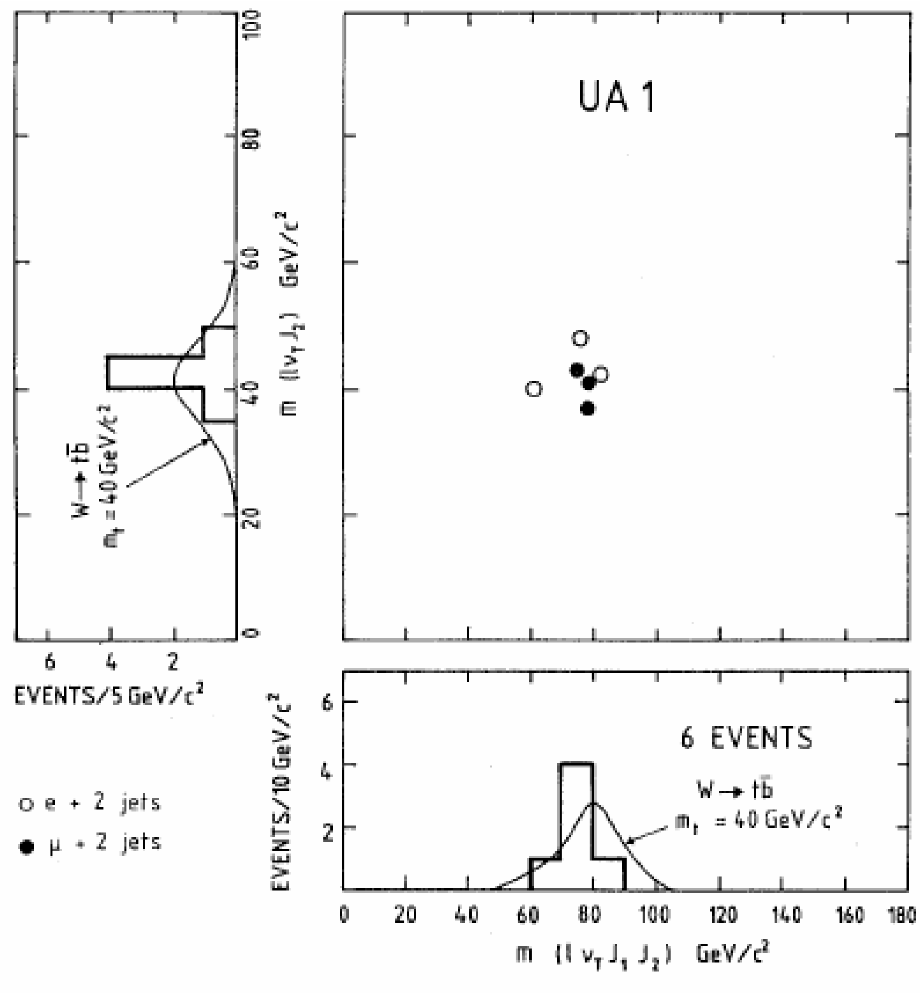
- **Signature is isolated lepton plus ME_T and two jets**
  - **Mass ($jl\nu$) should peak at m_t**
  - **Mass ($jjl\nu$) should peak at m_W**



$\lfloor\!\rightarrow$

What they found

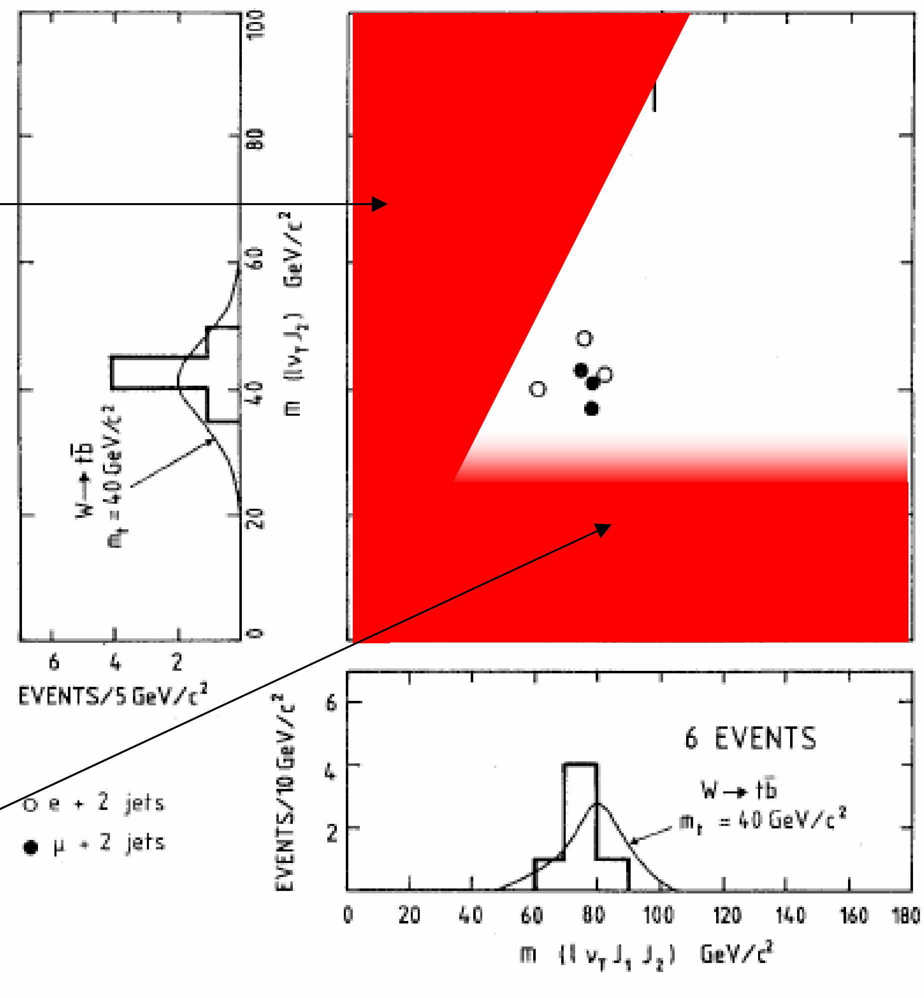
6 events observed
0.5 expected



JW (a young, naïve student):
"This looks pretty convincing!"

My advisor (older and wiser):
"Not necessarily…"

Hard to get $m(l\nu j_1 j_2)$ below $m(l\nu j_2)$ + 8 GeV
(since p_T^{j1} > 8 GeV)

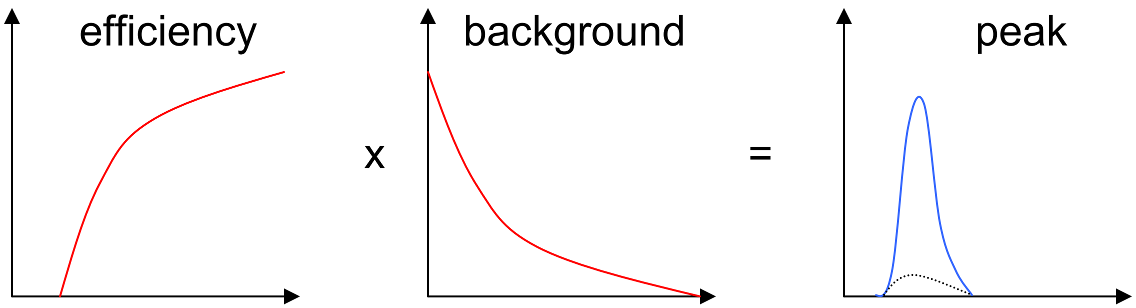


Hard to get $m(l\nu j_2)$ below 24 GeV
(since p_T^l > 12 GeV)

In fact 30–50 GeV is typical for events just passing the p_T cuts

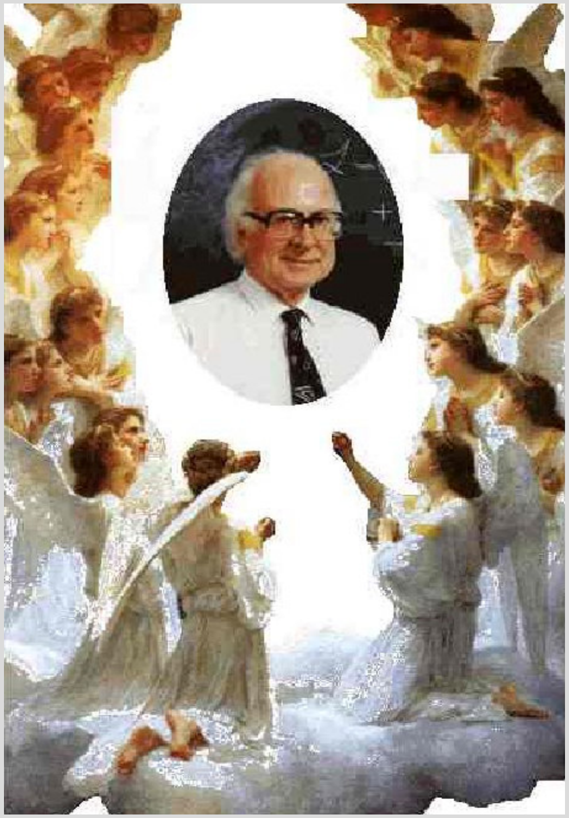
The moral

- If the kinematic cuts tend to make events lie in the region where you expect the signal, you are really doing a "counting experiment" which depends on absolute knowledge of backgrounds



- UA1 claim was later retracted after analysis of more data and better understanding of the backgrounds (J/ψ, Y, bb and cc)
  - In fairness, the knowledge of heavy flavor cross sections and the calculational toolkit available at that time were much less complete
  - Final limits from UA2 (UA1): $m_t > 69$ (60) GeV

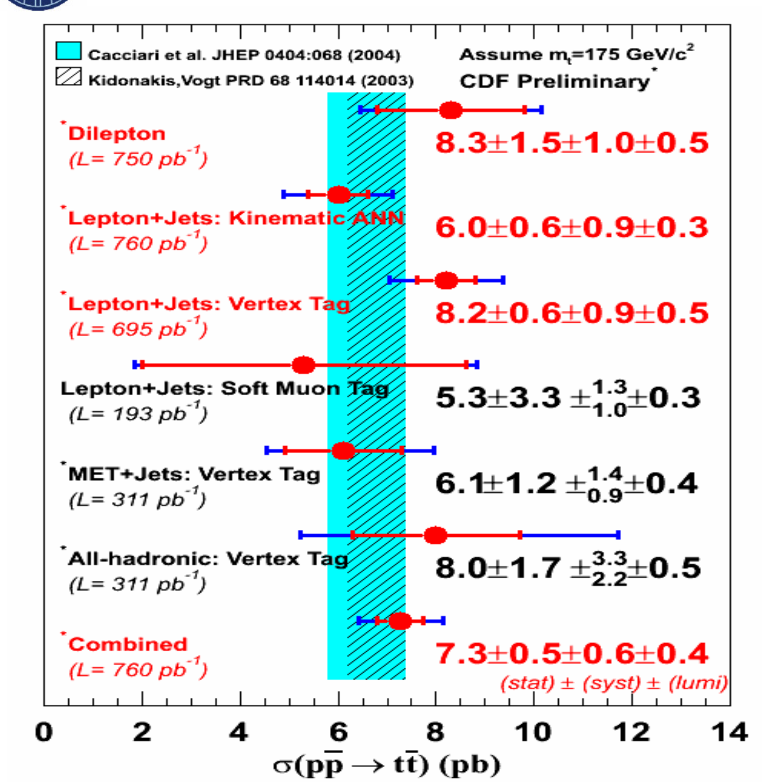
After Discovery…

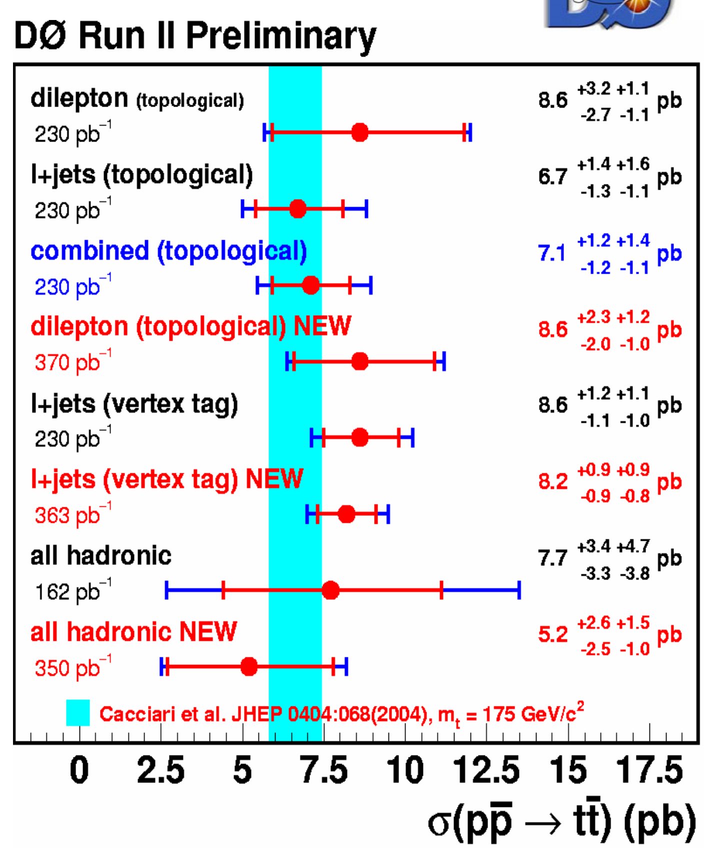


(thanks to Mark Oreglia)

- Once a new state has been discovered…
- Want to
  - Verify production mechanism (cross section, kinematic distributions)
  - Verify decay modes
  - Measure mass
  - Measure quantum numbers (spin, charge…)

Top Cross section measurements

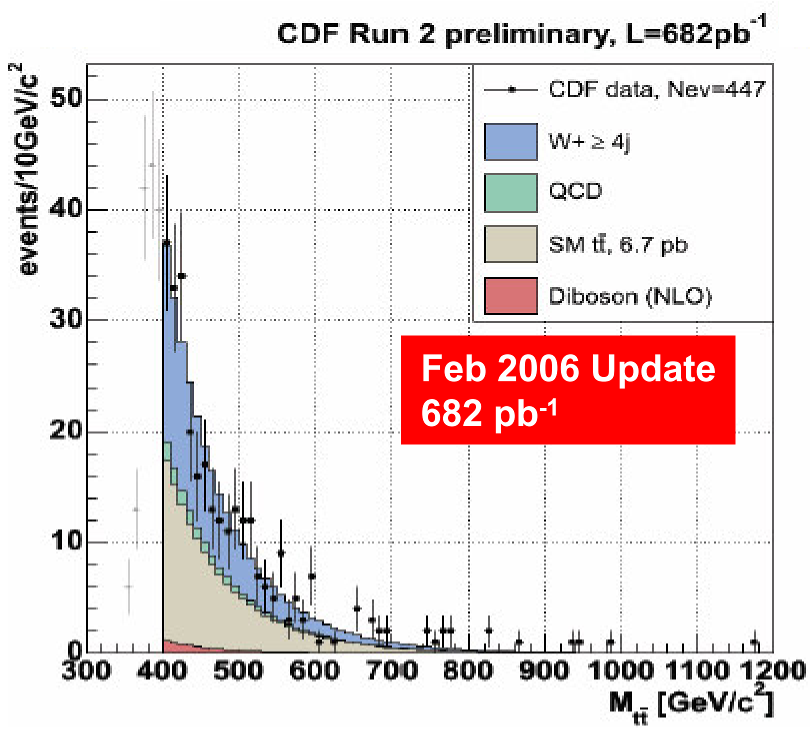


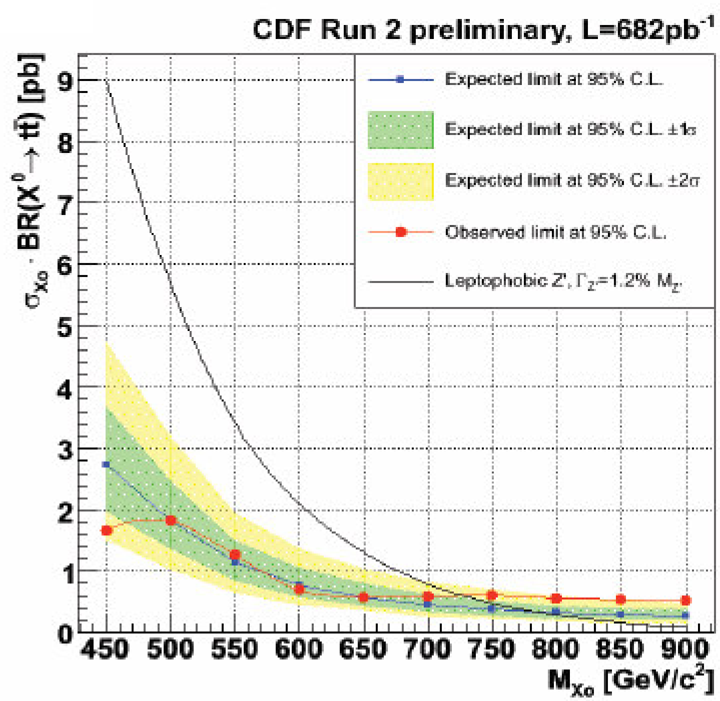


- All channels consistent with each other and with QCD
- Ongoing effort to combine measurements within and among experiments.

New particles decaying to top?

- One signal might be structure in the $t\bar{t}$ invariant mass distribution from (e.g.) $X \to t\bar{t}$

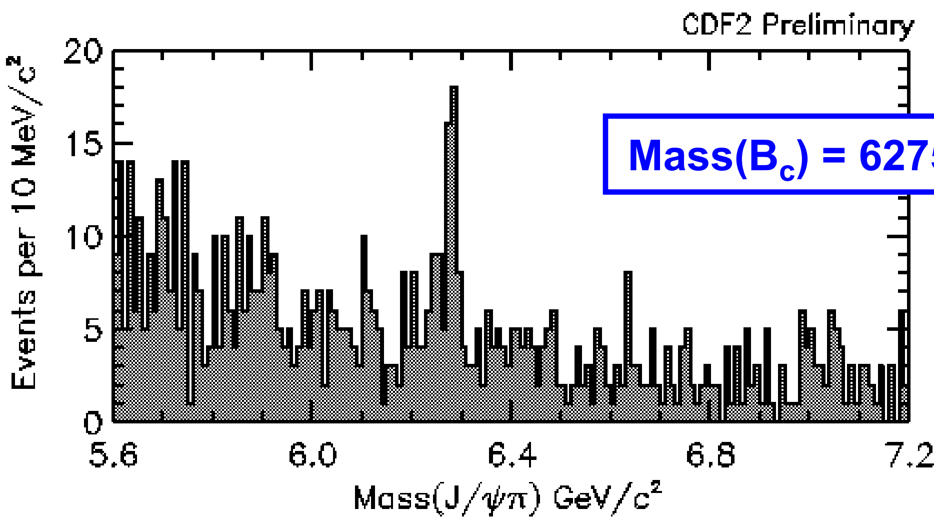




- Consistent with QCD

Mass measurements

- Straightforward for a clean final state with all particles reconstructed:



Mass(B_c) = 6275.2 +/- 4.3 +/- 2.3 MeV/c^2

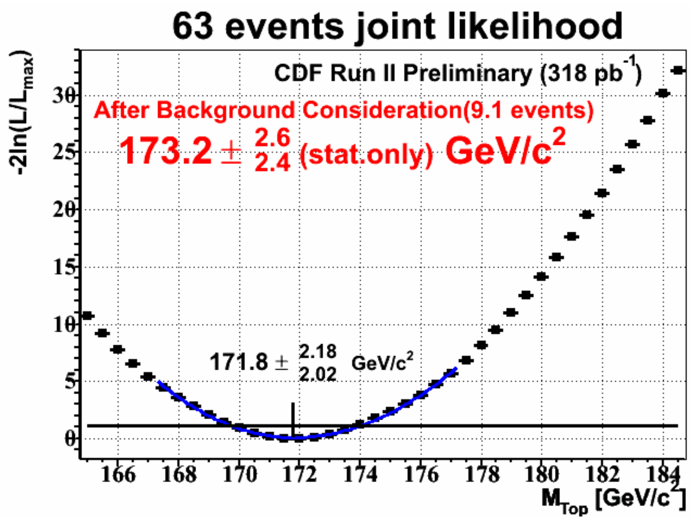
- Harder if there is missing energy involved, multi-step decay chain(s), jets (jet energy calibration becomes an issue) and combinatorics (which jet comes from which particle)
  - Often the case at LHC, especially for supersymmetry
  - Again, top is an example

Extracting the top mass

Two basic techniques

- "Template method":
  - extract a quantity from each event, e.g. a reconstructed top mass
  - find the best fit for the distribution of this quantity to "templates"

- "Matrix element" (or "dynamic likelihood") method
  - Calculate a likelihood distribution from each event as a function of hypothesised top mass, including SM kinematics, and multiply these distributions to get the overall likelihood
  - The "ideogram method" is a simplified version of this technique

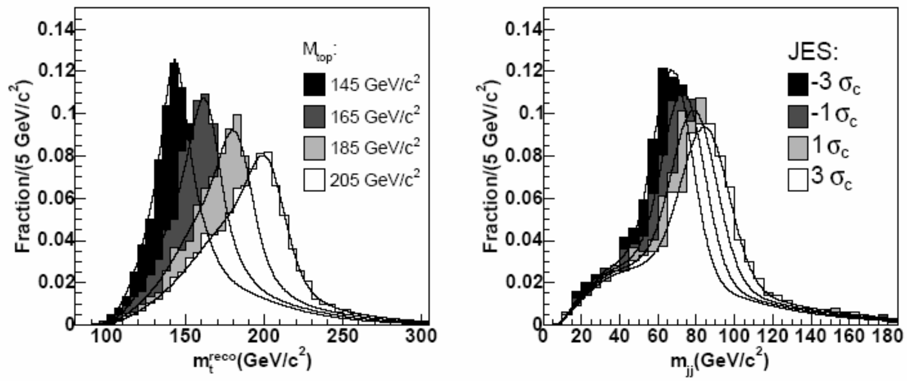


Jet energy scale

- The jet energy scale is the dominant uncertainty in many measurements of the top quark.
- CDF and DØ use different approaches to determine the jet energy scale and uncertainty:
  - CDF:
    Scale mainly from single particle response (testbeam) + jet fragmentation model
    Cross-checked with photon/Z-jet p_T balance
    - ~3% uncertainty, further improvements in progress.
  - DØ:
    Scale mainly from photon-jet p_T balance.
    Cross-checked with closure tests in photon/Z+jet events
    - Run II calibration uncertainty ~ 2%

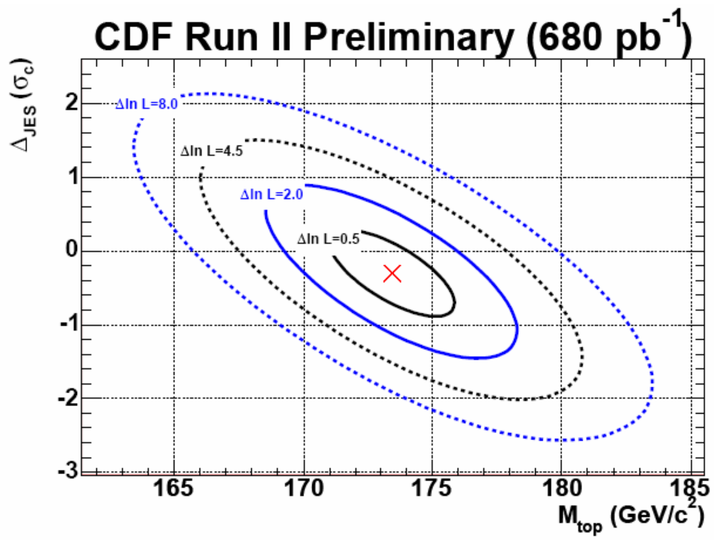
Top mass

- **Both experiments are now simultaneously calibrating the jet energy scale in situ using the $W \rightarrow jj$ decay within top events**



Combined fit to

top mass
and
shift in overall jet scale
from nominal value



But …
no information on E_T or η dependence, or on b-jet scale (these become systematic errors)

CDF lepton + jets
template method

Top mass status Summer 2006

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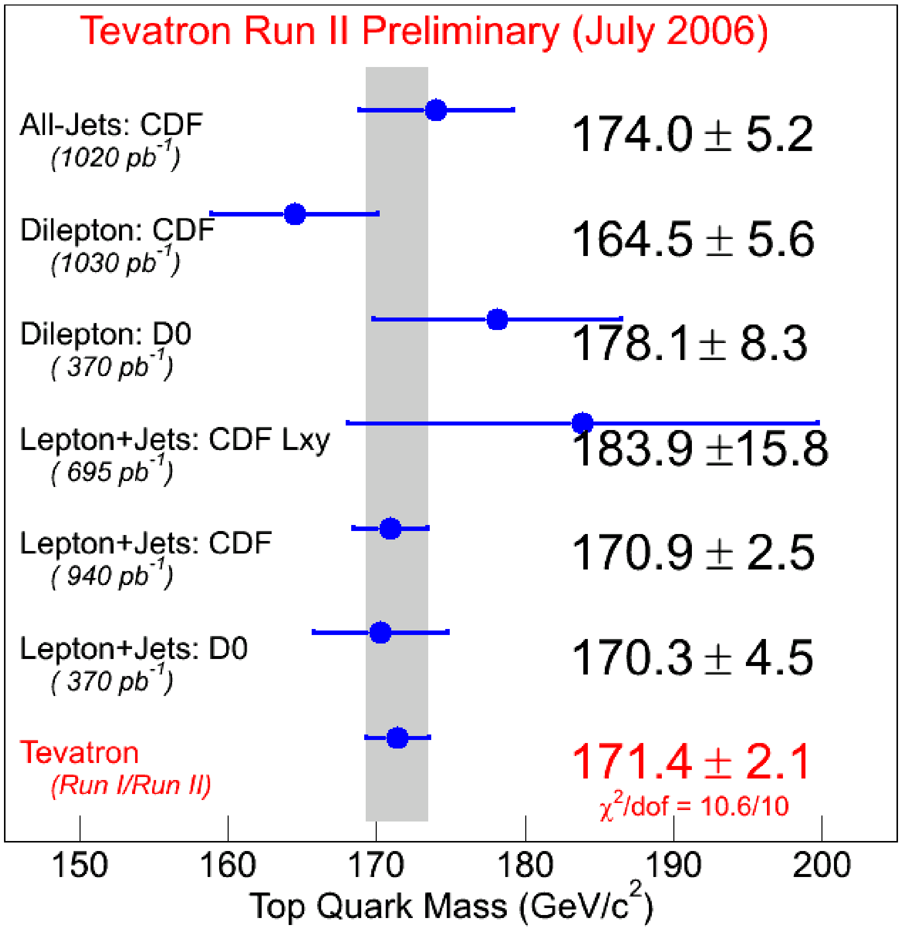
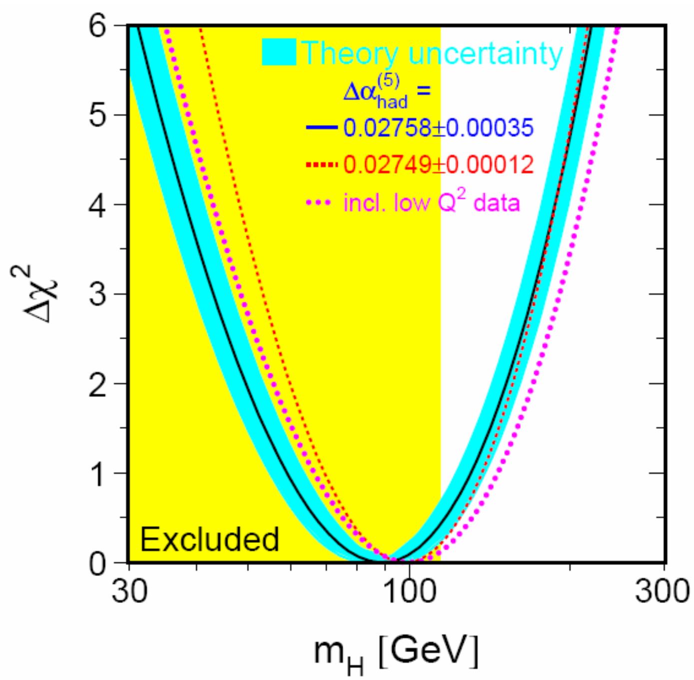
http://tevewwg.fnal.gov



Most precise measurements come from lepton + jets

Use of W → jets calibration is an important improvement



$$M_H = 89^{+39}_{-28}\,\text{GeV};\ M_H \begin{cases} < 199\ \text{GeV (95\% of allowed range)} \\ < 166\ \text{GeV (95\% CL for fit)} \end{cases}$$

How does top decay?

- In the SM, top decays almost exclusively to a W and a b-quark, but in principle it could decay to other down-type quarks too

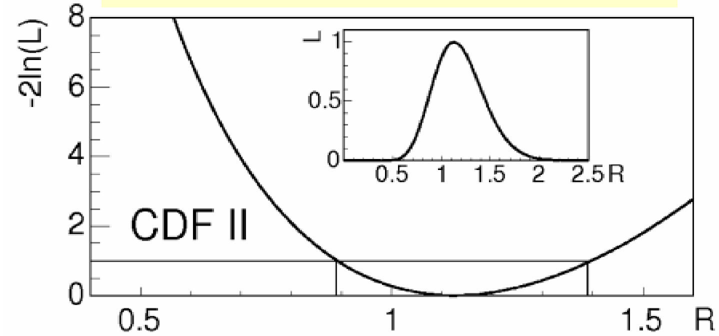
- Can test by measuring

  $R = B(t \to b)/B(t \to q)$

- Compare number of double b-tagged to single b-tagged events

All consistent with R = 1 (SM)
i.e. 100% top $\to$ b

Lepton+jets and dilepton (~160 pb^{-1})



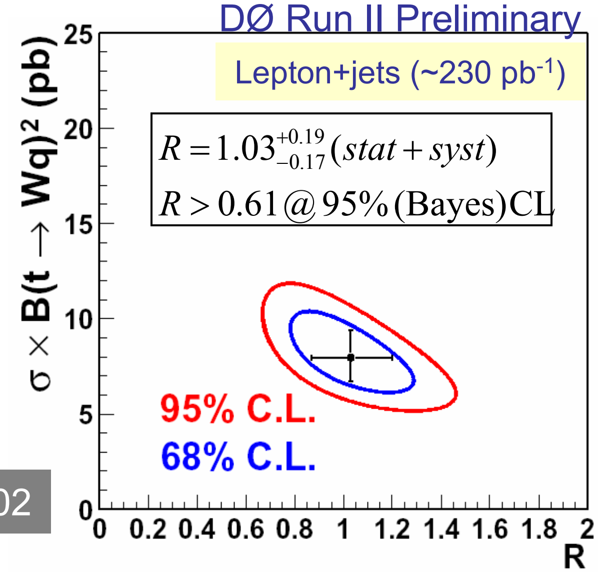
PRL 95 102002

$R = 1.12^{+0.27}_{-0.23}(stat + syst)$
$R > 0.61 @ 95\%\ (F \& C)\ CL$

DØ Run II Preliminary

Lepton+jets (~230 pb^{-1})

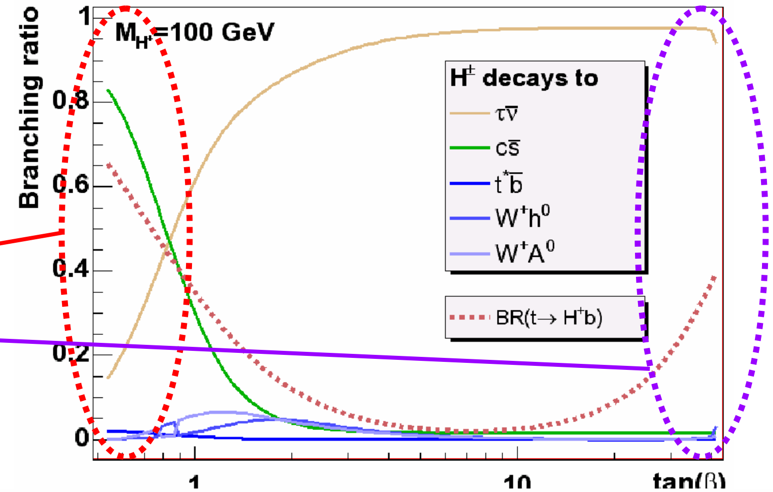
$R = 1.03^{+0.19}_{-0.17}(stat + syst)$
$R > 0.61 @ 95\%\ (Bayes)\ CL$



hep-ex/0603002

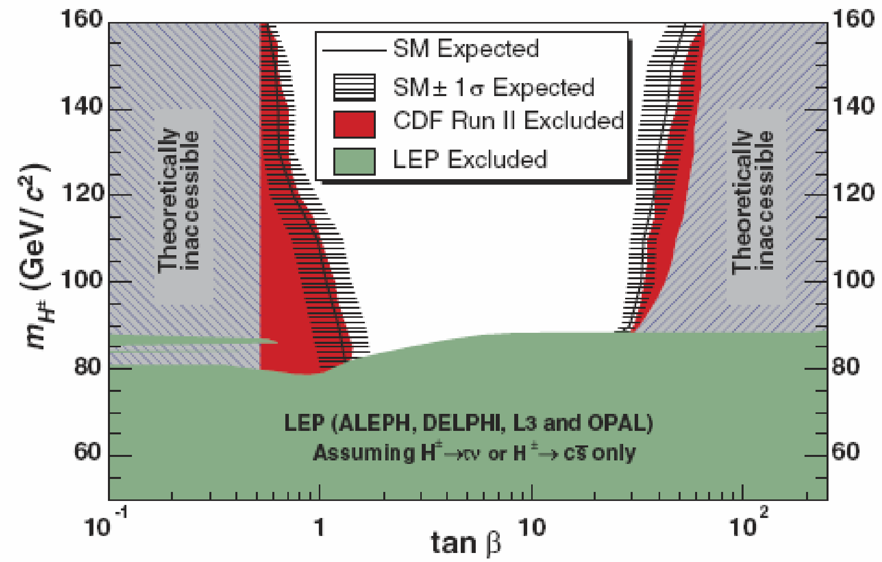
Top → charged Higgs

- If $M_{H\pm} < m_t - m_b$ then $t \to H^+b$ competes with $t \to W^+b$
- Sizeable $B(t \to H^+b)$ expected at
  - low tanβ: $H^\pm \to cs$, Wbb dominate
  - high tanβ : $H^\pm \to \tau\nu$ dominates
- different effect on cross section measurements in various channels.



- CDF used σ_{tt} measurements in dileptons, lepton+jets and lepton+tau channels
- allowed for losses to $t \to H^+b$ decays
- Simultaneous fit to all channels assuming same σ_{tt}

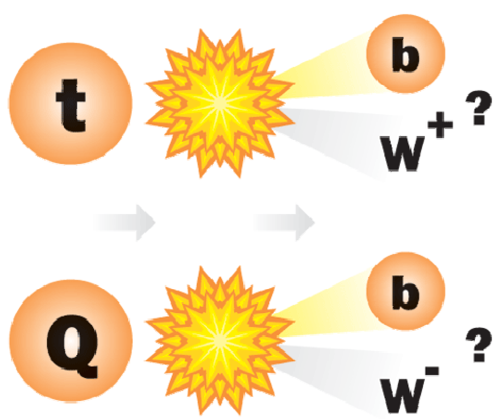
But still room for substantial $B(t \to H^+b)$ – as high as 50%?

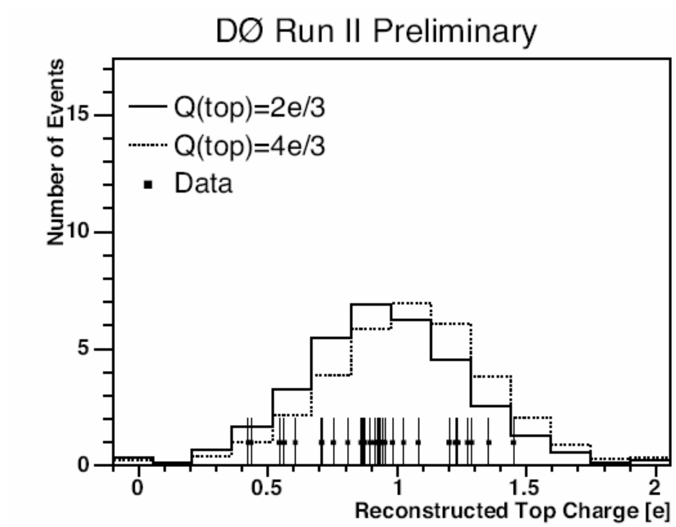


PRL 96, 042003

Top charge

- Using 21 double-tagged events, find 17 with convergent kinematic fit
- Apply jet-charge algorithm to the b-tagged jets
  - Expect b (q = –1/3) to fragment to a jet with leading negative hadrons, but $\bar{b}$ (q = +1/3) to fragment to leading positive hadrons
  - Jet charge is a p_T weighted sum of track charges
  - Allows to separate hypothesis of top $\rightarrow W^+b$ from Q $\rightarrow W^-b$





- Data are consistent with q = ±2/3 and exclude q = ±4/3 (94%CL)

Spin in Top decays

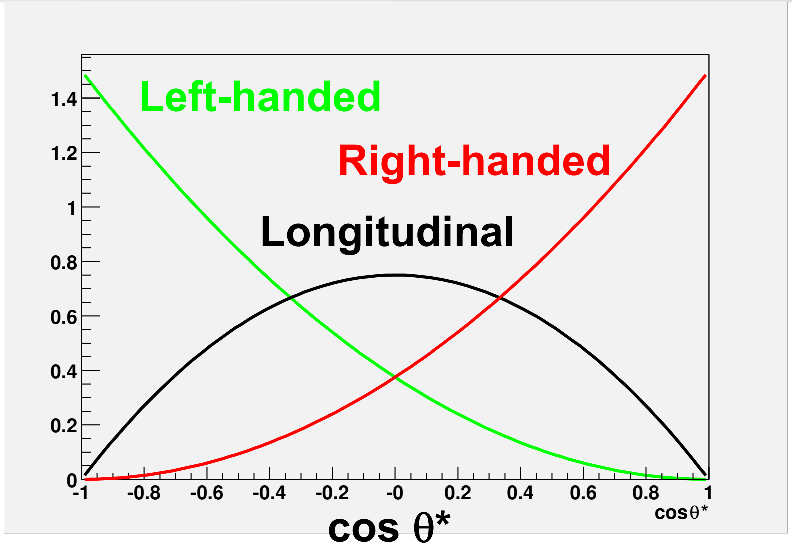
- Because its mass is so large, the top quark is expected to decay very rapidly (~ yoctoseconds)
- No time to form a top meson
- Top $\rightarrow$ Wb decay then preserves the spin information
  - reflected in decay angle and momentum of lepton in the W rest frame
- We find the fraction of RH W's to be (95% CL)

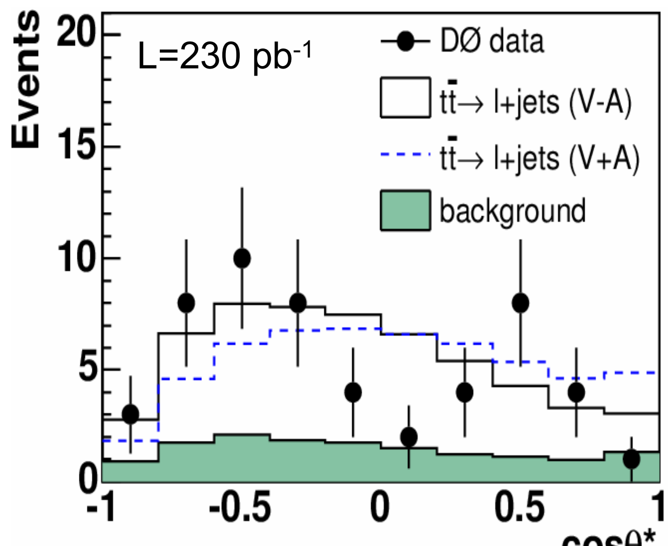
  $F_+ = 0.08 \pm 0.08 \pm 0.05$ (DØ)
  < 0.09 (CDF)

  CDF finds the fraction of longitudinal W's to be

  $F_0 = \quad 0.74 + 0.22 - 0.34$
  (lepton p_T and $\cos\theta^*$ combined)

  In the SM, $F_+ \approx 0$ and $F_0 \sim 0.7$



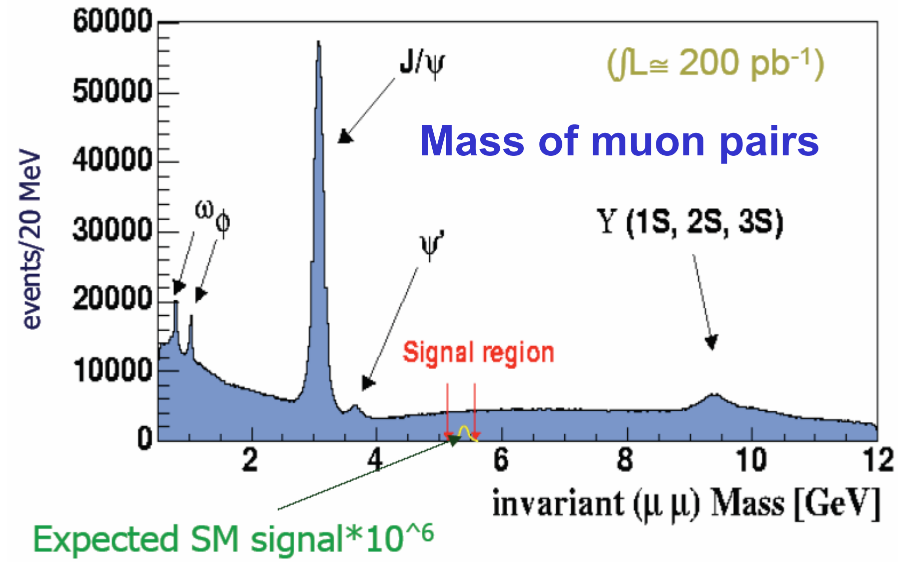


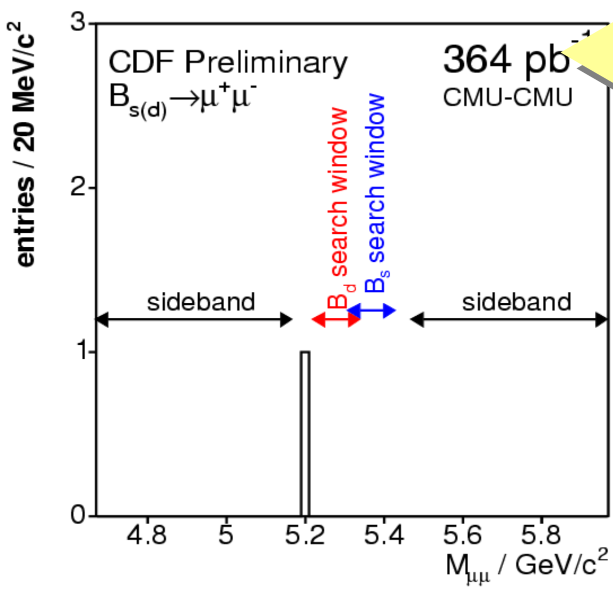
PRD 72, 011104 (2005)

All consistent with the SM

Blind Analysis

- **Example:**
  the rare decay of B_s and $B_d \rightarrow \mu^+\mu^-$
- **In the Standard Model, cancellations lead to a very small decay probability**
  - **3×10^{-9} and 10^{-10}**
- **New particles (e.g. SUSY) contribute additional ways for this to happen, increase probability**
  - **up to 10^{-6}**





"blind analysis": hide the signal region

- **Optimize cuts on side bands in mass**
- **Open box – is there a signal?**
  - **In fact find no events**
  - **Set limits**
  - **Constrain SUSY models**

A few words on Systematic Errors

- Estimating systematic errors is not an exact science
- Need to be honest – not over conservative, not over aggressive
  - Sometimes there's a tendency to overestimate errrors to "cover our butts" for things we forgot
  - Remember, theorists are liable to add your systematic error in quadrature with the statistics, input it into a χ^2 fit and expect χ^2/DF ~1
    - assumes $\pm 1\sigma_{sys}$ is a 68% confidence interval
  - While we often tend to think of the systematic error as more like a 95% (or 100%) interval
    - e.g. "How far off could we be?"
- Need to be clear what we did and how we estimated the numbers we quote

Example: top mass

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CDF note 8375

Source of systematic uncertainty	Magnitude (GeV/c^2)
Residual JES	0.42
b-JES	0.60
Generator	0.19
ISR	0.72
FSR	0.76
b-tag E_T dependence	0.31
Background composition	0.21
PDF	0.12
Monte Carlo statistics	0.04
Lepton p_T scale factor	0.22
Multiple Interactions	0.05
Total	1.36

Possible Variation with E_T or η (change by $\pm 1\sigma$)

How different from light quarks?

PYTHIA vs. HERWIG

Vary parameters in generator

Change by $\pm 1\sigma$ in estimated efficiency

Change backgrounds by estimated undertainties and vary model of W+jets

Divide sample

Shift lepton p_T by $\pm 1\%$

Room for MC not to model properly

- **Be prepared for a significant amount of work!**
  Each line in this table is essentially a re-analysis of the top mass

Conclusions

- The only way to learn physics analysis is by doing it.

- To your great good fortune, you (as students and postdocs) have the opportunity to carry out cutting edge analysis at forefront facilities – as a routine part of your careers.

  – Seize this opportunity and enjoy it!

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Questions, comments…